BRITISH WELDING JOURNAL

1959 JUNE

VOL. 6 NO. 6

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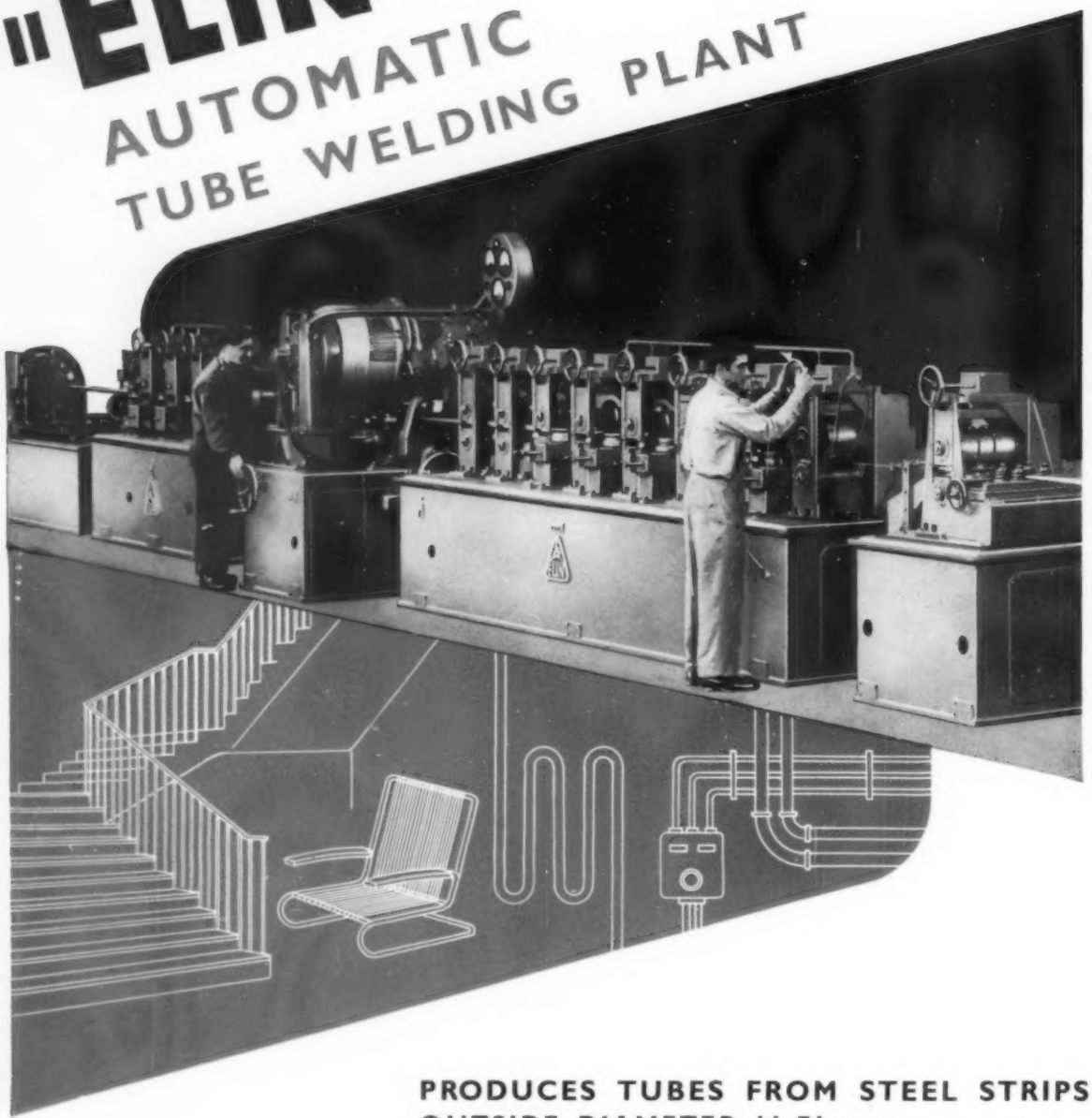
Discussion at Autumn Meeting 1958

Review of Welding Exhibition

"ELIN"

AUTOMATIC TUBE WELDING PLANT



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Inside front cover

Spinning

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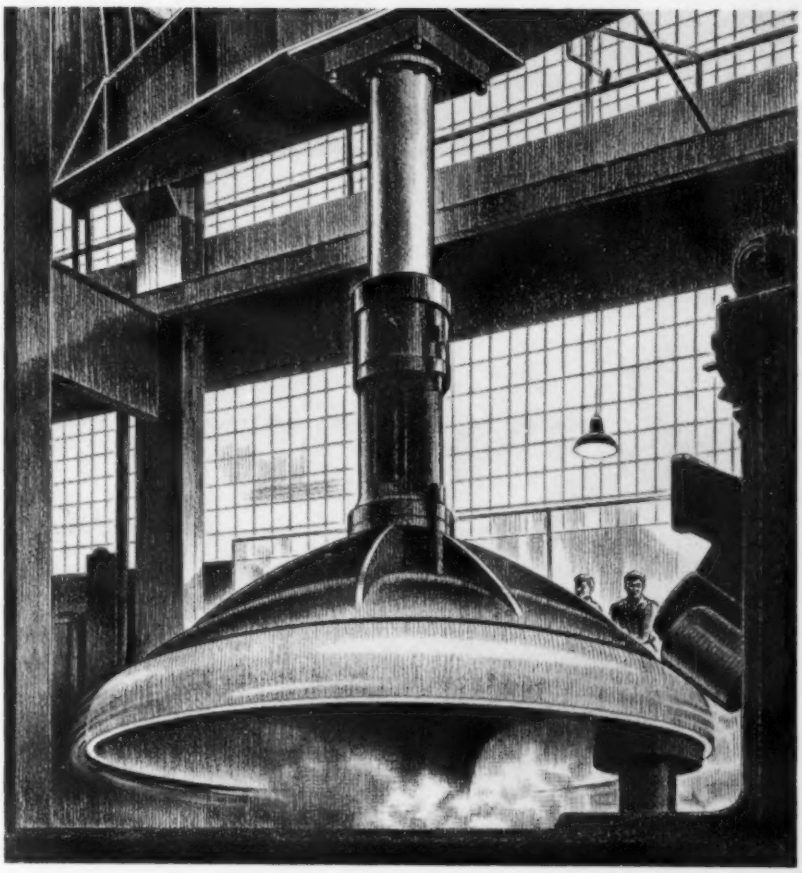
- CUTS TOOL COSTS



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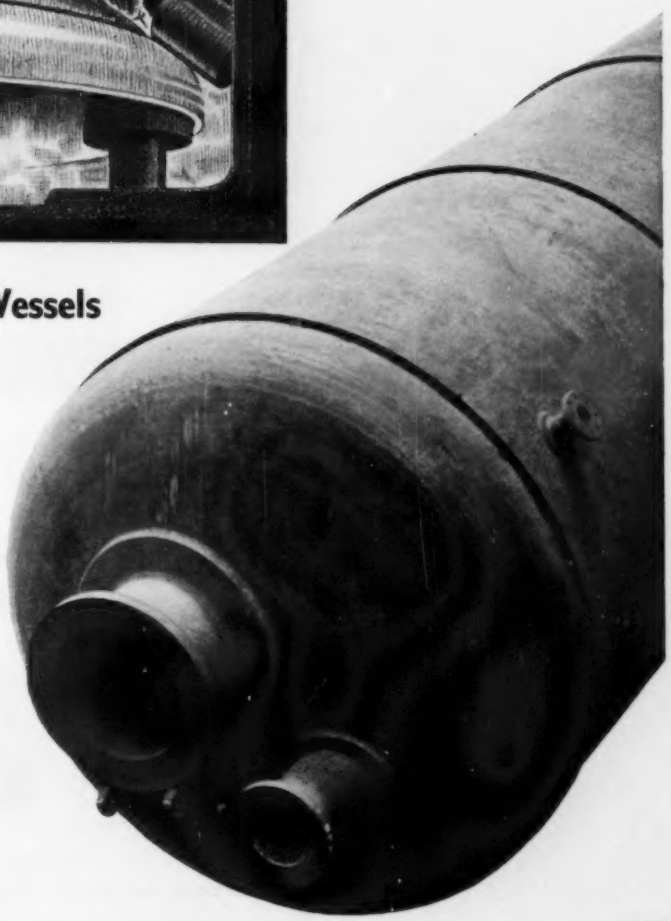

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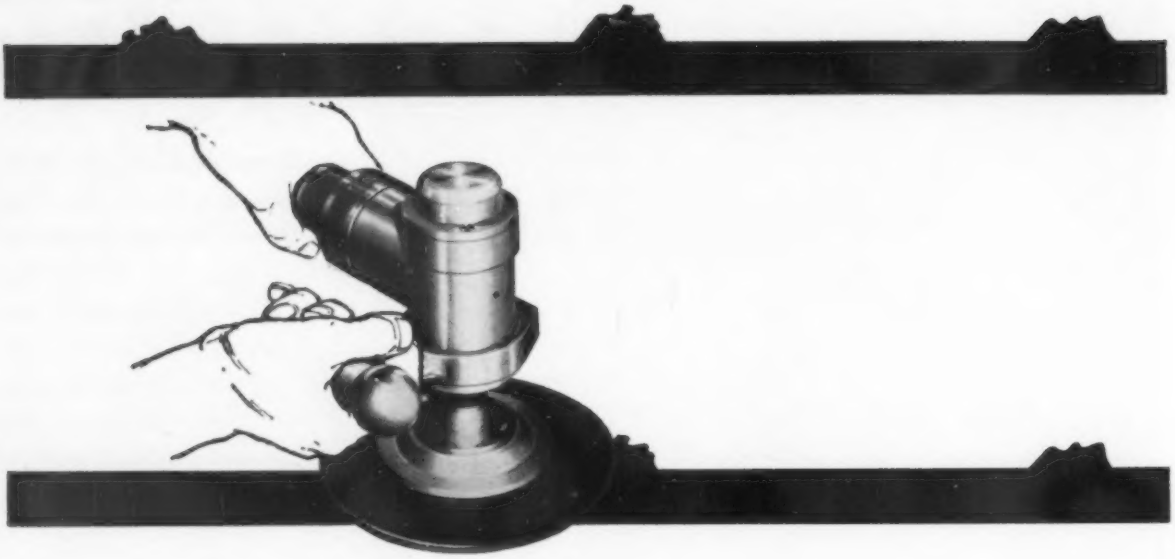

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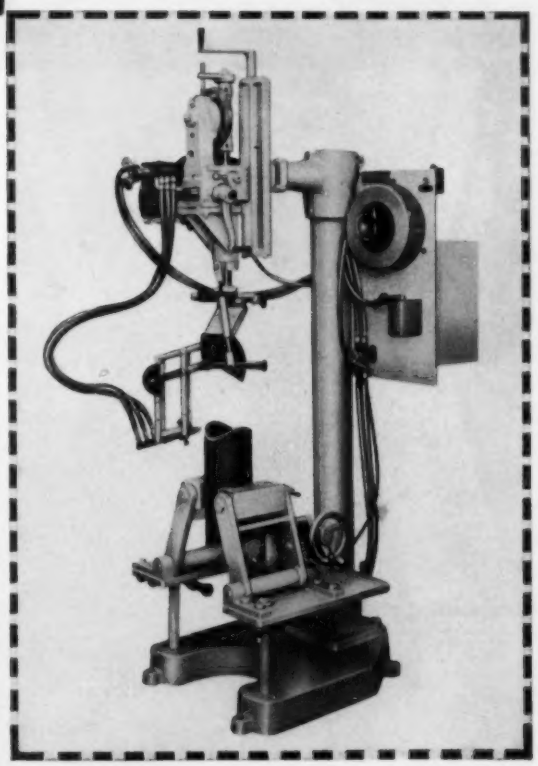

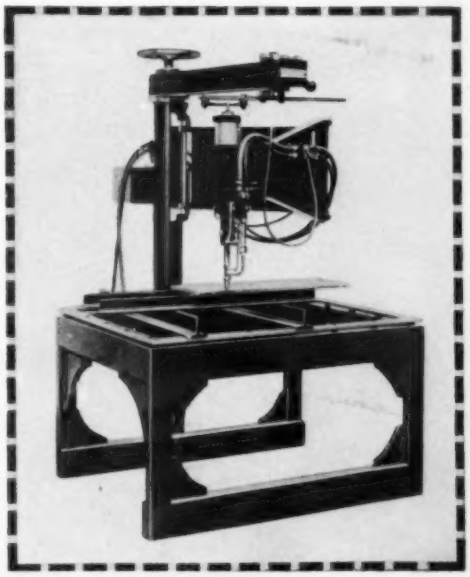

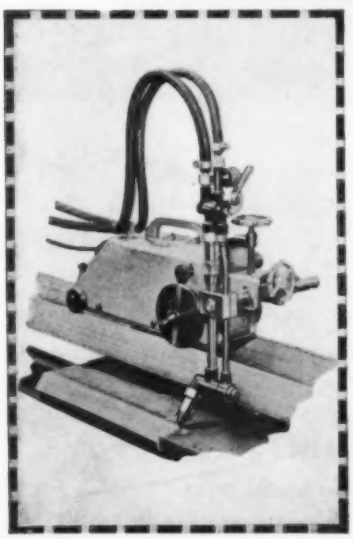

The ingeniously designed 'Vic' automatic pipe profiling and bevelling machine (*above*) automatically prepares pipes ready for welding.

The 'Comet' profiling machine (*left*) with electro-magnetic roller is of the elbow arm type permitting cutting in every direction.

The 'Creeper' machine (*bottom left*) is designed for straight line and circle cutting and has forward and reverse motion.

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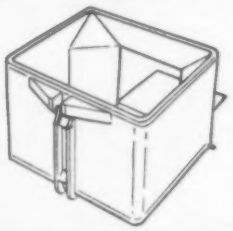
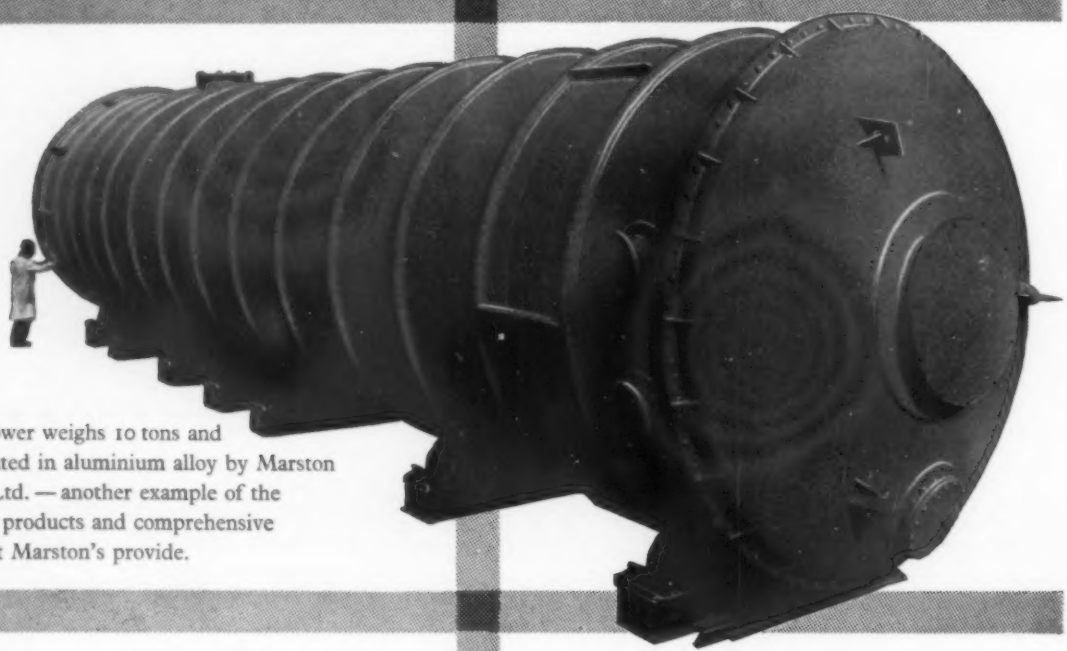
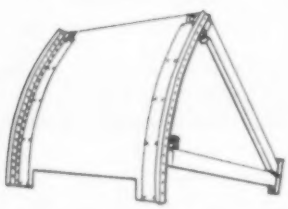


This truck-container is designed to carry granular material of particle size approximately $\frac{1}{16}$". Special attention had to be paid to the fit of the door and the smooth finish of the interior. The body ($\frac{3}{8}$" plate 'Kynal' M 39/2) was welded by the argon arc and Argonaut processes.



This 52' tower weighs 10 tons and was fabricated in aluminium alloy by Marston Excelsior Ltd. — another example of the specialised products and comprehensive service that Marston's provide.



This radial sluice-gate is 6' 6" wide and 6' high. It is made of aluminium alloy, to minimise maintenance costs. To obtain a clean design free from any crevices where corrosion might start, the gate was welded by the argon arc process. It is believed to be one of the first examples in this country of a radial sluice-gate in welded aluminium alloy.

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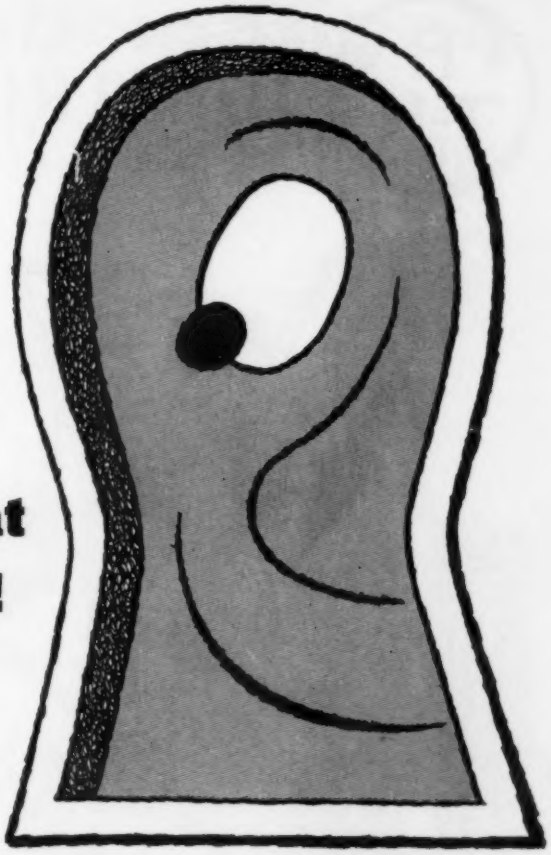

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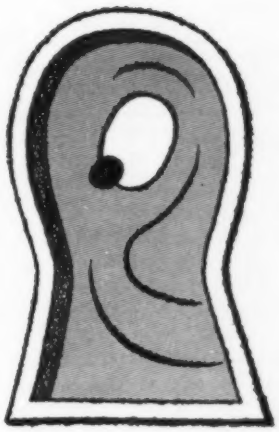

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BK 24	1200	140	—
BK 24A	1200	140	Integral
BK 24B	1200	140	Clamp on
BK 34	2400	355	—
BK 34A	2400	355	Integral
BK 34B	2400	355	Clamp on
BK 42	600	56	—
BK 42A	600	56	Integral
BK 42B	600	56	Clamp on
BK 66	300	22·4	—

* Ratings are for welder control service and refer to two valves in inverse parallel at any voltage from 250-600v. r.m.s.

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Type	Maximum peak voltage (Kilo volts)	Maximum average current at peak voltage (Amps.)
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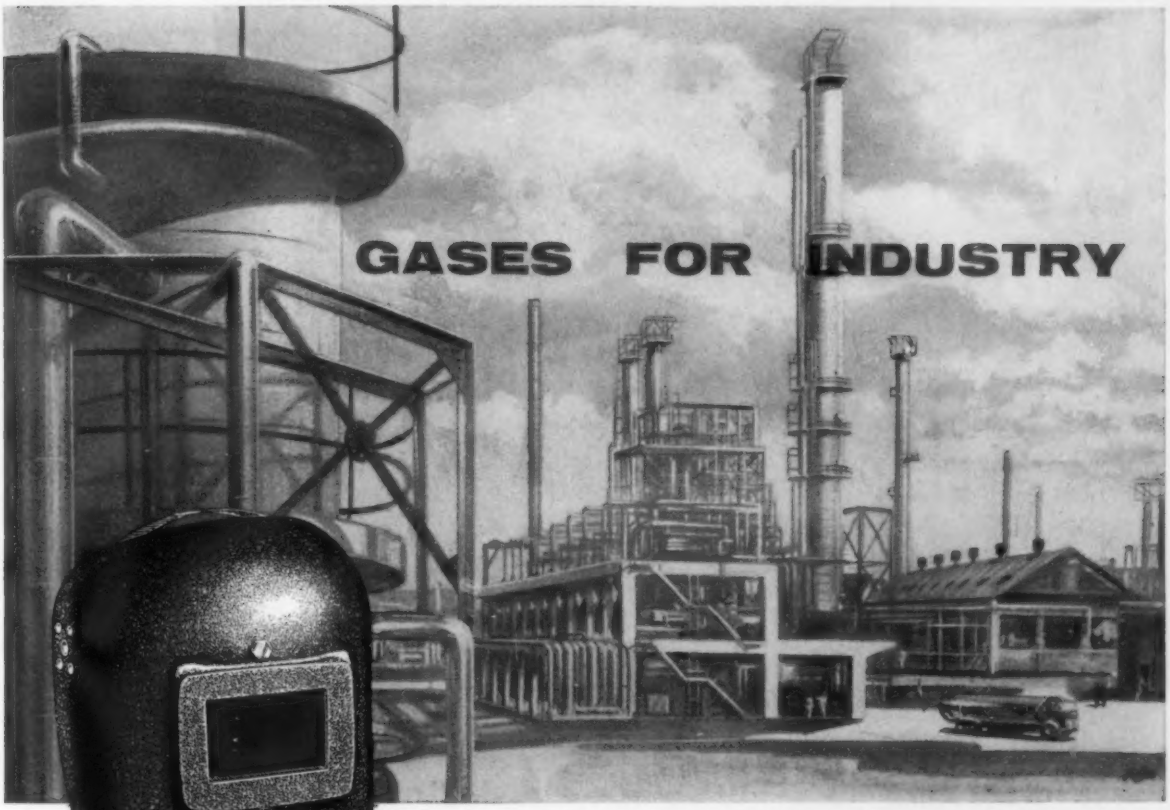

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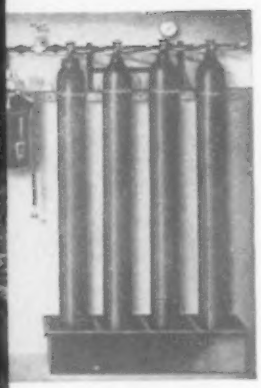
SIG.1A

Photograph illustrating the FUS.ARC.CO_2 process by courtesy of Quasi-Arc Limited



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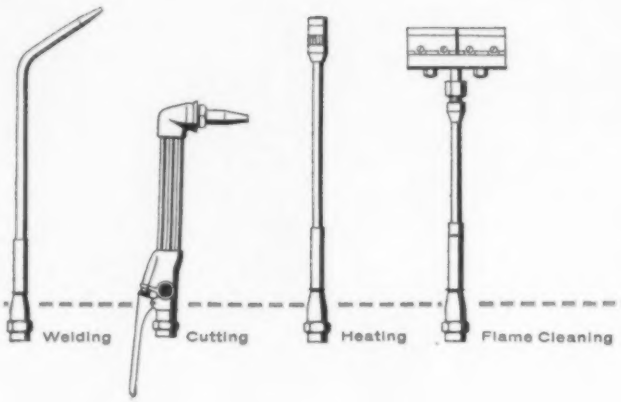

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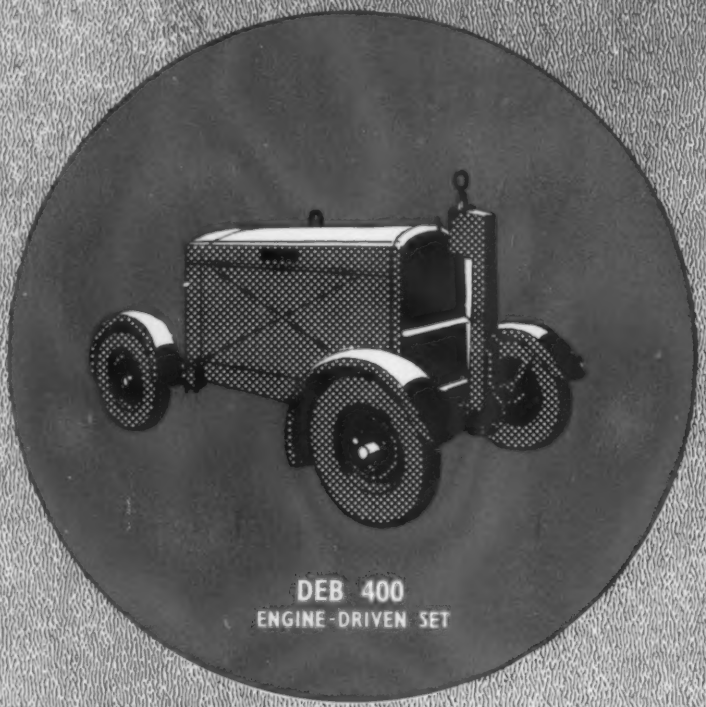

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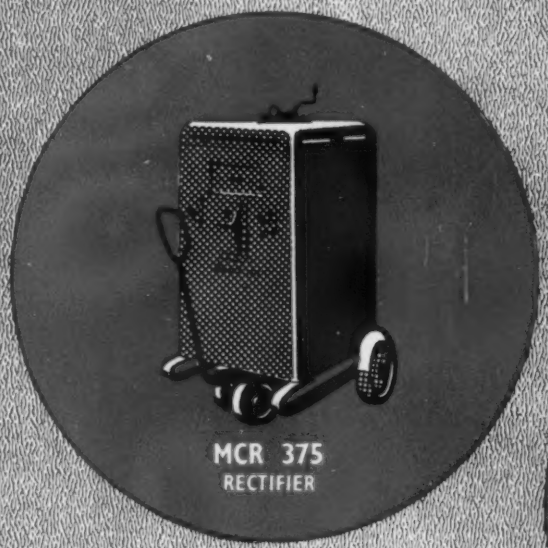

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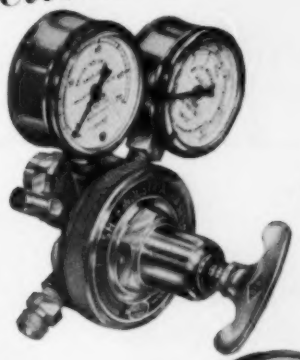

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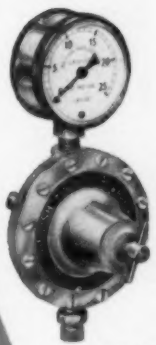

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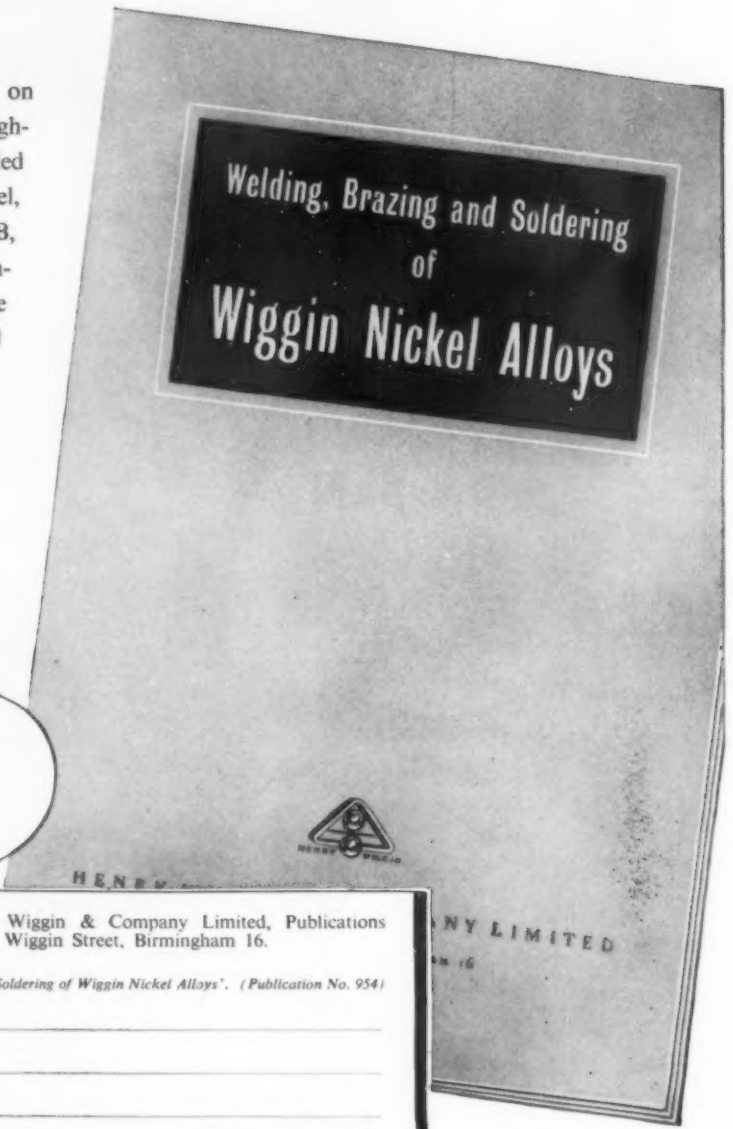

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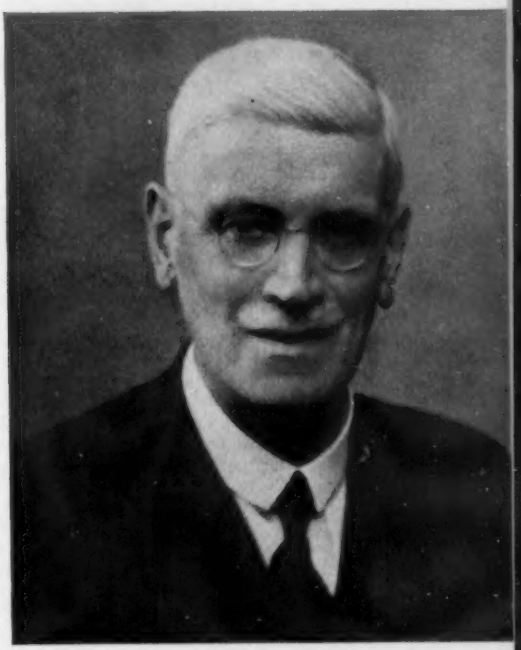
1875–1959



SIR WILLIAM JAMES LARKE, who died on 29th April, a few days after his eighty-fourth birthday, held a unique place in the minds and hearts of members of the Institute and the British Welding Research Association, to both of which he gave nearly a quarter of a century of eminent service.

It was in 1935, when he was Director of the National Federation of Iron and Steel Manufacturers, that Sir William, deeply convinced of the national importance of research in welding, accepted a Vice-Presidency of the Institute and the Chairmanship of its Technical Development Committee. The international Welding Symposium of that year, convened by The Iron and Steel Institute and supported by all the leading engineering Institutions, had formulated a programme of fundamental welding research. The task to which Sir William addressed himself was to transform the Institution of Welding Engineers, a twelve-years-old institution with well under 1000 members, into an effective instrument for the organization of research. His influence won the reconstituted Institute the support of other leading engineers, among them Sir Alexander Gibb, who became its President, and secured financial backing from industry and a grant from the Department of Scientific and Industrial Research. With the late Mr. A. Ramsay Moon as its Secretary, the Institute was set on its new course, attracting to its membership and to service on its Research Committee engineers and metallurgists with the foresight to see some way into the future of processes most generally regarded with suspicion by their contemporaries.

In 1937 Sir William succeeded Sir Alexander Gibb as President of the Institute and so began the Institute's longest and probably most onerous Presidency, lasting five years and covering the removal of the Institute's offices from Victoria Street to Buckingham Palace Gardens, the outbreak of war, the virtual suspension of normal Institute activities between 1939 and 1942, and the transfer of Ramsay Moon, then Secretary and Director of Research, to organize the Welding Advisory Service of the Ministry of Supply.

With the fund raised to mark the Institute's gratitude for his Presidency, Sir William endowed the Medal which bears his name, the premier award of the Institute.

The demands of war on the welding processes proved how far-sighted had been Sir William's advocacy of welding research and emphasized the inadequacy of the provision made for it. The Department of Scientific and Industrial Research pressed for the separation of the Welding Research Council from the Institute and its transformation into a Research Association independent of the professional body. So the British Welding Research Association came into being in 1946, with Sir William Larke as its first President and Mr. Ramsay Moon as its first Director of Research. Sir William remained the very active President of the Association until four years ago, and until last year continued to put at the disposal of the Institute and the Association the ripe fruits of his long and distinguished career as an engineer and administrator. He served on the Committee to which the Institute's Council entrusted the formulation of its future policy in 1956, and its recommendations owe much to his advice.

On the occasion of his eightieth birthday, in 1955, the Institute conferred its Honorary Fellowship on Sir William and with the British Welding Research Association organized a luncheon, with Sir Claud Gibb in the Chair, to do him honour. In the illuminated address then presented to him, the two bodies justly recorded their debt to his long leadership and the debt which the nation owes him for his timely grasp of the significance of the welding processes.

In his speech at the luncheon Sir William quoted, as expressing his own mind, the prayer

> "*Lord, give me work till my life shall end,*
> *and give me life till my work is done.*"

A man of his forward-reaching mind would perhaps always see some task waiting for his hand, but all who were privileged to know him will be thankful that he found so much to claim his interest and his energy for so long. His wife died on 10th January last, after a long illness and in the sixtieth year of their marriage. Those who knew with what devotion he cared for her in the years of weakness and suffering may feel that for him perhaps both parts of his prayer were granted.

Our sympathy goes out to his son, Mr. W. M. Larke, his daughter, Miss J. Larke, and to all his family.

Autumn Meeting 1958

The Autumn Meeting of the Institute of Welding was held in London from Wednesday to Friday, 5th to 7th November 1958, commencing with the Annual Dinner at the Park Lane Hotel on the evening of 5th November.

There were four technical sessions held at the offices of the Institute on the Thursday and Friday, for the presentation and discussion of papers. The Chairman at the first session was the President, Mr. J. Strong. The Vice-President, Mr. E. Seymour-Semper, took the chair at the second session. The Chairman at the third session was Professor G. Wesley Austin, and at the fourth Dr. E. G. West.

The Presidential Address (see December 1958 issue of the Journal*) was delivered by Mr. Strong at the opening of the Thursday morning session, a vote of thanks being proposed by Mr. Seymour-Semper.*

Development of the Tungsten-arc Cutting Process*

By R. A. Cresswell

Mr. **A. R. Moss** (Ministry of Supply, Fort Halstead): The section on "Economic Considerations" omits the most significant factor—that users of tungsten-arc cutting equipment may have to pay a high royalty for the shielding gas used, and may also be subjected to a severe licensing agreement. If this is not correct would the author please state the present terms? If it is basically correct, widespread use of the process will be restricted and welding engineers and scientists may have to examine the patent literature more thoroughly and also think twice before publishing their results.

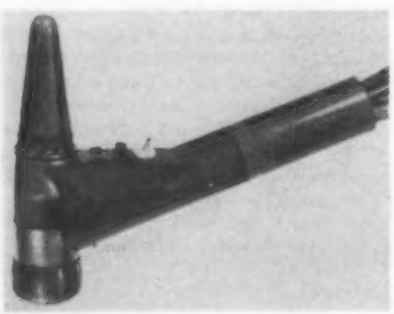
The value of the paper would have been enhanced by the inclusion of references to some of the early work on constricted-arcs, to fundamental researches and to patents. For example, to the important American patent application No. 524,353 (1955) and final patent No. 2,806,124 (1957).

Groups of workers in Great Britain have been engaged on plasma-jets, constricted-arcs, and similar researches for some time and several different electrical-discharge devices have been developed. An early device developed in the Ministry of Supply is shown in Fig. *A*. This is a 100 kVA model designed for manual operation and is suitable for cutting metallic or non-metallic materials; adjustments to current, etc., may be made from the built-in control panel. Certain cutting operations are facilitated by passing a portion of the gas through a central electrode containing a fine hole.

Would the author please state:

(i) In what fundamental manner does his arc torch differ from the American model?
(ii) Can oxygen-rich gas mixtures be used?
(iii) Which method was used for detecting nitride?
(iv) What are the advantages and disadvantages, for mild steel, of tungsten-arc cutting compared with oxy-acetylene cutting?
(v) What nozzle diameters were used and what were the kerf widths corresponding to the plate thicknesses given in Tables 1 and 2?

* *Brit. Welding J.*, 1958, vol. 5, p. 346



A—*Plasma jet torch developed at Ministry of Supply*

Author's Reply

Dr. **Cresswell** (in reply): The economic considerations in my paper are general and do not refer to such matters as the patent situation and royalty payments. I would refer interested parties to the commercial side of my organization for such information.

The paper set out to outline the developments in which I was concerned personally and not to cover much history. The constricted arc is by no means novel and was brought to notice by the work of Gerdien in 1922* and has been the subject of a number of patent applications. One of these, British Pat. No. 391,422 by Wist (void) dates back to 1930. In recent years the various aspects of constricted arcs have been revived and studied by workers in Great Britain and many other countries, particularly the U.S.A.

I would reply to Mr. Moss' final five queries as follows:

(i) The present torch, although of British design, does not differ fundamentally from the American torches. It uses a pilot arc to aid arc striking and a water cooled copper replaceable nozzle.

(ii) Oxygen-rich gas mixtures cannot be used to replace the nitrogen/hydrogen gas because of the obvious detrimental effect of severe oxidation of the tungsten electrode.

* H. Gerdien and A. Lotz: *Wiss. Veroff. Siemens-Konz*, 1922, vol. 2, p. 489; 1935, vol. 14, p. 25

(iii) Metallographic examination of the metal near the cut surface and of weld metal after welding revealed no evidence of nitride. The cut surfaces of aluminium are perfectly clean, and no observable oxide or nitride film can be seen.

(iv) Comparison between oxy-acetylene cutting and arc cutting of mild steel involves two main factors, surface quality and speed of cutting. It is difficult to achieve a perfectly square dross-free bottom edge with arc cutting, and so gas cutting scores here. On intermediate thicknesses, arc cutting is faster but can be used only up to a thickness of some 3 in. Arc cutting may compete economically on, say $\frac{1}{4}$–1 in. thick material but would only be attempted if a good enough edge could be achieved. Kerf widths with arc cutting are wider than with oxy-acetylene.

(v) The nozzle diameter used throughout the trials referred to in Tables I and II was $\frac{1}{8}$ in. Kerf widths were of the order of $\frac{1}{4}$ in. at the top and $\frac{5}{16}$ in. at the bottom of the cut.

Developments in the Inert-gas Tungsten-Arc Fusion Spotwelding Process* *By F. W. Copleston and L. M. Gourd*

Mr. **J. A. McWilliam** (Firth-Vickers Stainless Steels Ltd.): I confirm the importance of good contact between the mating surfaces to be welded, for I have found that if insufficient pressure is applied the weld is not very good.

Should the thickness on which the test welds were made be $\frac{3}{16}$ in. and not $\frac{1}{8}$ in. (p. 396)? In Fig. 7 the complete penetration is shown at about 0·190 in. or about $\frac{3}{16}$ in..

The welding of 16 s.w.g. stainless steel to $\frac{3}{4}$-in. thick mild steel is a very interesting application. Was the material the same 18/8 niobium-bearing steel referred to in other parts of the paper? Another question is whether there is any dilution from pick-up of the mild steel backing in the fused zone, for the carbon content may sometimes run up to 0·25%.

Any such dilution would reduce the resistance to corrosion of the spots, and I suggest that the welding of a second 18/8 Nb sheet on top of the first might be considered. This could be rather thinner than the first—16 s.w.g. as shown for the first one and 20 s.w.g. for the second one. The 20 s.w.g. thickness would also have the advantage of increased flexibility in a vessel that was subject to a considerable temperature range.

Mr. **B. E. Dorey** (British Welding Research Association): In Table I, I note that the average spot diameter for comparable weld strength is smaller for tungsten-arc spotwelding than for resistance welding. I assume, therefore, that the tests were made under identical conditions. But is the quoted average argon spot weld diameter measured at the top surface of the weld, or is it the nugget size?

Could the authors also explain why these weld strengths are higher, particularly in the 16 s.w.g. size where the argon spot appears to be very much stronger than the resistance weld?

In Fig. 1 what is the significance of the light coloured lines or rings which have formed at right angles to the dendrites? Are they associated with the crater-filling sequence?

It is encouraging that the authors have emphasized the importance of electrode end profile and arc length. In the early development of this work, on which I was engaged, it was found that this type of arc is very easily deflected if the hot spot on the electrode is not at the very tip. For rapid and accurate striking the arc must initiate from the extreme tip of the electrode and not somewhere up the side.

It was also found that the argon flow is very critical. Too great a flow will make arc initiation difficult because of turbulence and excessive cooling. Too small a flow will provide insufficient shielding.

In some American literature it is advocated that both grinding and subsequent polishing of the electrodes will help to increase the striking ability and also ensure longer life for the electrode.

In regard to crater filling, there is a very strong arc force when welding at the full current, which will tend to form a crater. As the current is reduced, the arc force on the molten metal is considerably reduced, thereby allowing the pool surface to rise.

The remarks on p. 396 concerning duty cycle or arcing time factor are perhaps a little misleading as regards equipment. If the authors mean that by using a higher current per spot it was possible to produce a greater number of spots per minute, I would agree.

In Mr. Waller's paper the rectifier plant is quoted as having a maximum continuous hand welding current of 115 amp. Then it would be seriously over-run at 180 amp, unless there is a considerable pause between each spot weld to ensure that the arcing time factor is well below 75%.

I assume that a smaller bore argon shield results in a deeper penetration into the sheet material and vice-versa. What is the practical minimum diameter of shield, and therefore how close is it possible to approach a corner or edge of a sheet? Also, how closely is it possible to place adjacent welds with this process?

Mr. **S. G. Nash** (Bristol Aircraft Ltd). wrote: The authors are to be congratulated on a very succinct account of the latest developments in this method, given at what is still a relatively early stage in the state of the art. It might be of interest to recall that interest in it at Bristol Aircraft was actually initiated by the necessity to make the structural models that Mr. Copleston described, with their very limited access and required high standard of dimensional accuracy and external finish. No other method of construction offered the same flexibility in application. At Bristol Aircraft the process is known by the more utilitarian—if less euphonious—title of "puddle welding"!

In the section on "Operating Conditions" perhaps a little more emphasis might have been laid on the *maintenance* of correct form of the electrode, together with current, time and arc-length, as one of the major parameters controlling consistence, if not quality as well. In initial preparation of the electrodes, machine grinding is well worth while, if not essential, to achieve accuracy, particularly in respect of concentricity, and so is the provision of gauges for electrode form and setting.

While the results for arc-length effect are not questioned as they stand in Fig. 5, one would like to ask the lecturers to essay some further explanation, and whether the significance of the effect might not be better expressed by plots of interface area and penetration of weld against arc-length. Greater penetration, one feels, does not necessarily mean higher shear values, because differences of weld form can intervene, especially with dissimilar thicknesses and materials. Usually the long arc gives a flatter form of puddle, but one questions whether the interface is always less.

Perhaps a more complete assessment of arc-length effects will be possible when more results have accrued. Meanwhile, would Mr. Copleston agree that one can have all of the forms of weld as shown in Fig. *A*?

On the effect of electrode shape, Bristol experience would suggest that, after a very few welds, the penetration from electrode shape *D* would be greater than that from shape *B*. For long life under normal conditions, our preferred electrode form has a 10° inclusive angle with a radiussed tip. Only under the abnormal condition of extremely long-

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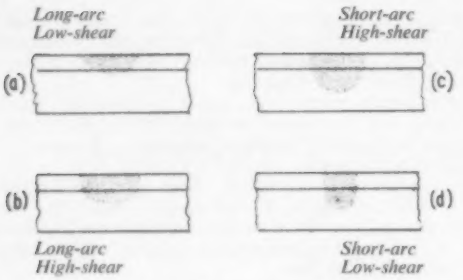
* *Brit. Welding J.*, 1958, vol. 5, p.394



A—*Various argonarc spot welds*

time cycles for each weld do we prefer to use a truncated electrode, with 45° included angle, to achieve a longer electrode life.

Bristol experience with 2% thoria electrodes has been satisfactory, but it is believed that there was some American experience of disintegration after short runs at high currents, on a.c. argon-arc welding. Have the authors any reservations of mind on this score with this method?

On shield design, one wonders if it is really the shroud bore that is affecting the penetration, or could it be the gas pressure? Pressure certainly can have a powerful effect on weld shape in displacing the metal from the weld centre, giving a sunk or dished shape, and, if high enough, even a blow-out. This could well be a progressive effect, the displacement of the molten metal from the weld centre starting with the initial current surge, giving thereafter less thickness to be welded during the remainder of the weld time cycle.

Finally, one looks forward to hearing from the authors on some future occasion, about their further development experiences, perhaps on a wider range of materials than those they have reported so far.

Authors' Reply

Mr. **Copleston** and Mr. **Gourd** (in reply): We would agree with Mr. McWilliam that the question of interface contact is of prime importance in the production of sound welds. It is not sufficient to rely on the manual, or in special cases mechanical pressure, applied by the torch, to bring the two surfaces into contact. The forming or preparation of the components must be such that the surfaces will come together without undue pressure. Attention to this feature will be repaid by the consistency of the results obtained from the process.

The material used for cladding the mild steel was 18/8/1 stainless steel, and we would agree that the use of a backing strip of similar material would reduce the dilution otherwise obtained. The degree of dilution obtained will depend to a great extent on the type of weld required to give mechanical properties suitable for the application.

When comparing the results quoted in Table I, it should be noted that the resistance weld figures are minimum values and could be increased by alteration of the nugget diameter. The diameters quoted for the argon-arc spot-welds were measurements of the weld nugget.

The 'ghost rings' seen in Fig. 1 are a typical macro-phenomenon and do not appear under high magnification. They are associated with the cooling cycle but cannot be directly related to the type of current decay system employed.

Mr. Dorey and Mr. Nash quite rightly draw attention to the importance of correct electrode preparation and the maintenance of the optimum form. We agree that every care should be exercised in the grinding of the electrode and are aware that the use of excessive current may melt the electrode end.

Shield design will in most instances be dictated by the position and degree of access to the weld. In all the work reported gas flow was kept constant, and any increase in penetration at constant weld conditions could be attributed to the increased gas pressure. Severe restriction of the bore of the shield will result in changes in the arc plasma itself and may radically alter the shape of the weld.

It is not essential to have an annular shield, for if the electrode and weld pool have adequate gas protection the electrode may be brought closely to any flange or adjacent component.

The effect of variations in arc length may produce weld forms as shown by Mr. Nash in Fig. *A*, but ideally a parallel-sided nugget is desirable. However, the weld geometry will be dictated by the type of joint required for each application, and arc length considerations may well be less important than those of current and time.

The equipment used in the work described would not be used commercially but a power source having a continuous rating of 200 amp would be recommended.

New Developments in Arc Welding Processes and their Applications* *By P. Shaw and D. B. Tait*

Mr. **R. G. Braithwaite** (Past-President): The average electrode used for site welding is by no means weather-proof. How do the iron-powder electrodes compare in this respect with the rutile and low-hydrogen types?

In regard to automatic welding, it is fair to say that in structural fabrication only about 12 to 14 lb of weld metal is generally needed for each ton of steel. Yet the tendency is to design new equipment to deposit ever-increasing poundages of weld metal at greater speeds and so completely overtake the ability of the rest of the department to handle and manipulate the material.

There seems to be room for the employment of lighter welding heads with considerably less power, using comparatively thin wires, and probably high density current of 500–600 amp. These machines could then be built into the normal manipulating machinery.

Concerning the use of combined gas and coated electrodes, do the authors really visualize that it will soon be possible to produce an automatic machine that will weld on steel in the veritcal and overhead position under site conditions?

Finally, I should like to know whether the bulkhead stiffeners shown in Fig. 15 were bulb angle sections with a rolled edge, for unless the shipyard workers are much more careful than the average structural engineer in mangling and flattening the plates before they start, there will be a considerable variation in the gap between the joint. Although the profiles of steel angles are closely specified in British Standards the edge is seldom constant. The conditions for welding fillets on each side of the stiffener are therefore different, and if the dual welding heads are provided with the same current and operate at the same speed there will probably be undercut on one side. Have the authors encountered these difficulties during the development of their machines and how have they been overcome?

Mr. **I. C. Fitch** (Metropolitan-Vickers Electrical Co. Ltd.): In Mr. Tait's comments on the use of the CO_2 welding process he mentions a deposit rate of 18 lb/hr. There have been recent claims in the U.S.A. of speeds up to 30 lb/hr, and although it is stated that the mechanical properties of the weld metal are still satisfactory, there seems to be little supporting evidence. Can Mr. Tait comment on these claims?

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* *Brit. Welding J.*, 1958, vol. 5, p. 454

Mr. **J. A. Lucey** (Quasi-Arc Ltd.): Some confusion has arisen about the precise nature of the vertical welding process as developed in Russia, owing to statements that there was a change from the arc welding process to an arcless process after a short interval of time. When welding is started underneath the burden of granulated composition there is a definite arc discharge between the tip of the electrode and the parent plate. The heating of the arc causes the composition to fuse, and with this vertical method of welding the fused slag level rises until it completely submerges the tip of the electrode. The passage of current then occurs through the molten slag and is not in the form of a true arc.

The essential features of this equipment are that it must provide the means of feeding electrode wire into the joint; there must be copper shoes for supporting the molten weld metal; and the rate of movement of the welding machines must be controlled to keep pace with the level of molten metal. Various methods for accomplishing this novel form of control have been suggested, including measurement of temperature at the copper shoes and also the possible use of a nucleonic device.

One simple and effective control mechanism makes use of the fact that with high current welding using comparatively thin wires, the burn-off rate of the electrode is considerably influenced by the length of the extension of the electrode from the contact tip (commonly known as the I^2R heating effect).

The mechanical properties of weld metal deposited by the vertical process are reasonably satisfactory except for impact, which in the stress-relieved condition is about 20 ft-lb, Charpy **V**-notch, at room temperature. A normalizing treatment will give improved values.

Authors' Replies

Mr. **P. Shaw** (Quasi-Arc Ltd.) (in reply): The welding equipment manufacturers will certainly have to bear in mind the development of lighter welding heads. So as to deal with the problem of handling the large quantity of material that it is possible to weld in a short time there is now a tendency to combine the manufacture of welding equipment with conveying equipment.

The answer to the question about the edge of the stiffener and the gap is that a gap cannot be tolerated, and the plate has to be brought up to the stiffener, however difficult that may be.

We anticipated a problem in regard to the shape of the lower edge of the stiffener, but in practice it has not proved of great practical importance. There is a tendency to get a slightly different weld shape on the side where the stiffener is rounded, but it is possible to control the two heads independently, and we find in practice that the operator, after he has had some practice in working the machine, can correct his weld shape during welding.

Mr. **D. B. Tait** (in reply): The tolerance to weather conditions of iron powder electrodes depends upon the type of covering in which the iron powder is incorporated. Both conventional basic low-hydrogen electrodes and low-hydrogen rutile iron powder electrodes can be affected by adverse weather conditions. Conventional rutile electrodes are very tolerant to weather conditions and this also applies to Class 1 cellulose iron powder electrodes which are being widely used on site even in adverse weather conditions.

Although automatic processes for vertical and overhead welding on site are not yet available they are the subject of intensive development work, and it is hoped that at least a vertical welding process will be available shortly.

In regard to Mr. Fitch's comments, the bare-wire/CO_2 process gives deposition rates below those of other automatic processes. Continuous covered electrode welding used with a CO_2 gas shield will deposit 35 lb/hr, and submerged arc welding will deposit 90 lb/hr.

Although bare-wire/CO_2 welding may give deposition rates between 18 and 30 lb/hr, it has yet to be shown that the process is acceptable on such joints as square edge butt welds, in regard to such factors as the shape of the weld reinforcement.

Why Weld Automatically?* *By I. C. Fitch*

Mr. **R. G. Braithwaite**: I cannot agree with Mr. Fitch's formula for the feed speed, for he assumes that the burn-off rate for a particular electrode is always a straight line. The burn-off rate is dependent on both current and voltage, and for the 500–1000 amp machines for automatic welding, where the mains loading differs greatly from that for ordinary manual arc welding, it would be better to deal in terms of heat energy input.

Mr. Gilbert Roberts recently produced some extremely useful diagrams on automatic welding output and speeds based on what he called the 'kilovolt ampere curve'. These seem to indicate that the formula is more of a logarithmic type. It is apparent that we need to know much more of what happens in the submerged arc.

The efficiency of the burn-off rate in automatic welding could probably be improved by attention to arc voltage characteristics and by using fairly high current densities. The physical effects of the molten flux bath should also be considered, for it is possible that increases in travel speed may be limited by the surface viscosity of the weld melt. More information is needed on the effect of small additions of various constituents, such as manganese, aluminium and the like, on the viscosity of the surface of the molten pool.

This viscosity may also affect porosity in weld metal. Most plate is just mill finished, and if welding is fast it is likely that gases picked up from oxides and slags on the rolled surface may not be able to escape quickly enough because of the viscosity of the weld metal.

The problem of guiding and controlling the arc where the edges are irregular is more serious with automatic welding than it is with the manual process, which can be controlled by the welder. Does Mr. Fitch visualize the introduction of some means of speeding up or slowing down the rate of travel to accommodate these irregularities?

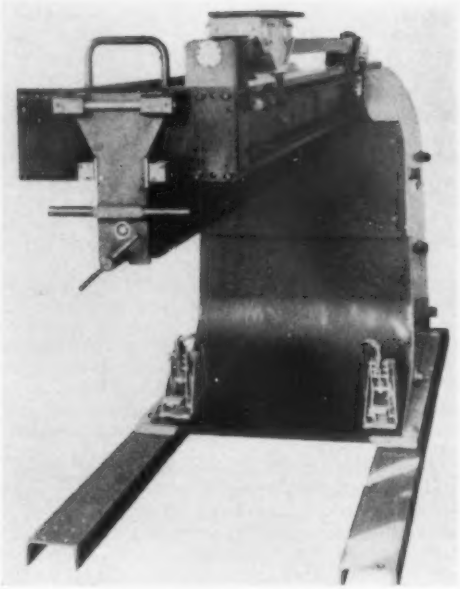
Mr. **F. Hirschmann** (Consultant): Quite a few shops which do not weld automatically today are those which cannot afford the special plant needed. I have therefore tried to offer to the welding shop an equipment which can be used for hand welding as well as for automatic welding. Such a plant should be rated for automatic welding at top setting, it must stand rough usage, and it must have a wide range.

The equipment shown in Fig. *A* is an oil-immersed rectifier. The oil tank contains the transformer, transductors and rectifiers; all the controls are on top. It is intended for hand welding, but is provided with built-in sockets, so that automatic controls, contained in a separate control box, can be plugged in. With such equipments, with a sufficient current reserve, it is possible to obtain with tungsten arc welding speeds of several feet per minute, with excellent results. A similar equipment can also be used for timed spot welds, with adjustments for the rate of the current decay and the timing.

The equipment shown in Fig. *B* is intended for automatic welding, although it can also be used for hand welding. It includes controls for the welding speed, the arc length and the rate of wire feed, as well as a device for reducing the

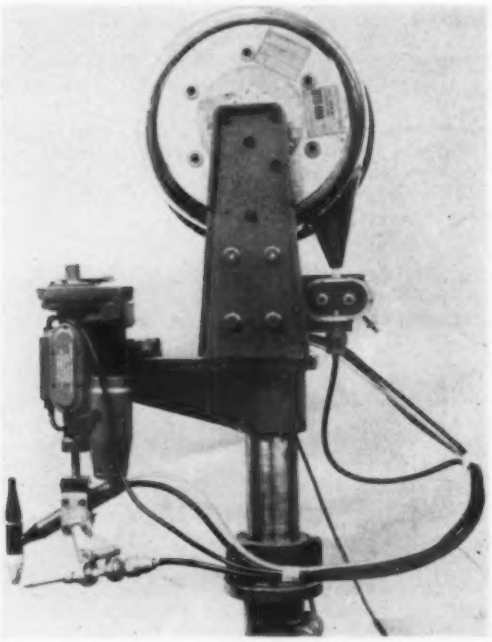
* *Brit. Welding J.*, 1958, vol. 5, p. 303.

A—*Oil-immersed rectifier*



C—*Welding jig for use with control equipment*

B—*Equipment for automatic welding incorporating cold-starting device*



D—*Mounted welding head with automatic torch actuator*

current at the start of the weld (so-called cold start), in addition to a crater eliminator. Here may be the answer to a question put by Mr. Needham in connection with Mr. Waller's paper. We often find, especially on light gauge material where no filler wire is used, or with consumable electrodes, a hole at the start of the seam. This is overcome by the cold start; the adjustable current reduction gives just as much heat as is wanted. The question of the current range was mentioned in the discussion; with the described plant the ratio of minimum to maximum current is 1:30, surely high enough for anybody.

Figure *C* shows a welding jig used in conjunction with the control equipment. The design is perhaps unusual in so far as it is heavier, and more like a machine tool than

orthodox equipment. The welding torch is mounted on a carriage which is moved by a motor driven lead screw on precision ground guide rails.

A welding head with a wire feed and automatic torch actuator is shown in Fig. *D*. It is mounted on a column like a radial drill; the same head can go on the carriage and be used for longitudinal welding.

Author's Reply

Mr. **I. C. Fitch** (in reply): I am entirely in agreement with Mr. Braithwaite's comments on the formula, but it is difficult to give a precise formula to accommodate all the conditions that apply in arc welding. The specific fusion rate for automatic welding of mild steel varies between 3 lb/hr/100 amp to 5 lb/hr/100 amp, depending on such variables as wire diameter, flux, welding current, polarity, and so on, but the approximate formula can still serve a useful purpose.

In regard to the accommodation of irregularities of preparation, some of the efforts which are being made by machine manufacturers have already been described, but those irregularities which demand a change in the speed of welding are much more difficult to accommodate. If preparation is allowed to be such that these irregularities occur they must either be compensated for automatically or one must depend more on the skill of the operator. At the present state of the art, I can visualize no very ready means of making automatically the sort of accommodation that Mr. Braithwaite would like to have.

Flame Cutting and Jigging for a Nuclear Power Station*

By J. W. Gethin

Mr. **E. Seymour-Semper** (Hancock & Co. (Engineers) Ltd.): This paper surely shows the extent to which oxygen cutting can be used today as a precision process, and this is particularly important when the development of new automatic techniques is demanding greater precision and closeness of fit-up prior to welding.

As welding has developed so oxygen cutting has developed, and as a manufacturer, I think I can say that we are keeping up with the demands for precision. The paper shows that modern equipment will cut curved plates, plates at an angle and other difficult variations in angularity and obliquity.

We recently designed and built for an atomic energy contractor, a rather 'fancy' machine which cuts holes for the moderator control rods in atomic energy reactors. The burner cuts a 16 in. dia. hole down the side of a sphere, and it has to go round, and up and down, varying its angle all the time so as to give a constant angle for the welding bevel.

Mr. Gethin also shows how far one can go in one's own works by a little ingenuity in design and adaptation of existing oxygen-cutting equipment.

Author's Reply

Mr. **Gethin** wrote in reply: As welding is developing at such a great rate and at the same time is putting an ever-increasing demand on the engineers and metallurgists for such stringent conditions of safety, the problems arising from these conditions will also continue to increase.

Oxygen cutting processes will therefore have to meet the same demands and must give conditions that ensure greater precision. Equipment will have to be developed and manufactured to operate for specialised applications; the 'special' machine will have to be developed and skilled operators will be needed to work them.

* *Brit. Welding J.*, 1958, vol. 5, p. 400.

Positioners for Automatic Welding of Atomic Reactor Housings* *By W. A. Davis*

(The paper was presented by Mr. C. C. Hanke)

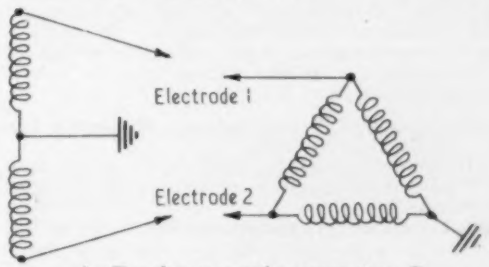
Mr. **P. Shaw**: In the past two years my colleagues and I have had to consider the particular problem of welding panels for spherical reactors. Could Mr. Hanke tell us whether the panels were held on to the frame by lugs welded on to them or by some other means? I have seen them held on by wire ropes and clamps.

Would he also comment on the advantages of 3-phase a.c. welding, for in Britain we have, on the whole, favoured the use of Scott-connected transformers to give a 2-phase output, one phase being fed to each head. Sometimes we have used d.c. on the leading head and a.c. on the trailing head, but this is a matter of personal preference.

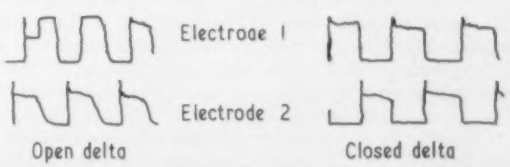
Mr. **P. T. Houldcroft** (British Welding Research Association): To avoid confusion, the terms 'positioners' and 'manipulators' should perhaps be defined a little more closely. I suggest that a positioner could be a piece of equipment which moves work into a position for welding and that it is stationary while the welding is carried out. A manipulator is a device which turns the work or moves the work while the welding is being done.

Some positioners are now becoming rather large, and it may be questioned whether we should not do more to make our welding processes work in awkward positions. It is, of course, very much easier to build a large positioner than to carry out the research and development needed for improvement of positional welding.

Mr. **J. L. Pratt** (Braithwaite & Co. (Engineers) Ltd.): We tried multi-phase welding of mild steel plate in 1954, using open-delta and closed-delta systems. The transformer



A—*Transformer secondary connections*—B



C—*Arc voltage oscillograms. (Note phase differences)*

secondary connections are shown in Figs. *A* and *B*. The electrode tips were spaced $\frac{3}{8}$ in. apart; typical arc voltage oscillograms are shown in Fig. *C*. Voltage magnification was not the same for each trace, so that comparison of arc voltages from the oscillograms is not possible in this instance.

A reactance was also tried in the earth lead of the system shown in Fig. *B*. A variable phase difference was then obtained between both electrodes, the amount depending on the value of the reactance. There is a current transfer from electrode to electrode as well as from electrode to plate; both vary according to the electrode phase difference.

* *Brit. Welding J.*, 1958, vol. 5, p. 449

No difference in the weld quality of submerged-arc welding of clean plate was observed; but it was possible to weld on rusty plate with no porosity. Deposition rates were naturally high, and arc stability was good with high-current-density electrodes. A Scott-connected transformer was not available to carry out further tests, and work was discontinued owing to the increasing complexity of the welding equipment needed.

Mr. I. C. Fitch: When welding with virtually bare wire on d.c., particularly when the electrode is of negative polarity, there can be very considerable changes in the rate at which the wire melts at a given current, according to the surface condition of the wire. If as-received wire is progressively pickled the melting rate may be ultimately increased two or three times. Conversely, by adding materials to the surface in quite small quantities, the melting rate may be reduced.

I do not suggest that all such wires would be satisfactory as welding wires, but it does seem from the discussion that a copper-coating may have a real effect on the rate of deposition.

Author's Reply

Mr. W. A. Davis: In all fairness to Mr. Shaw I should first state that we found the 3-phase welding not well suited for field work, and have since used d.c. welding sources—either motor generator sets or rectifiers. At least one of our shops still uses 3-phase submerged-arc welding to good advantage.

There are three basic 3-phase circuits for welding: (i) open delta; (ii) closed delta; and (iii) wye. The open-delta circuit was used in our case. Essentially, a phase goes to each of the two welding heads and a third phase goes to the work. The second welding head feeds its wire into the rear end of the molten pool in tandem behind the leading head.

Three-phase a.c. welding circuits have the following potential advantages:

(i) The use of 3-phase primary, eliminating heavy single-phase line loads
(ii) Two welding heads in tandem are used with several times the deposition rate compared with a single-tip head
(iii) The use of a.c. minimizes arc blow
(iv) Less power input per inch of completed weld is used particularly on heavier plates
(v) Each welding head and the earth phase can be controlled independently.

Potential disadvantages include:

(i) Increased number of variables, such as phase angle, phase sequence, power distribution between two heads, effect of primary power factor, and multiplication of controls for two welding heads plus the earth
(ii) High open-circuit voltages.

We found that for most field work the complex operation with so many variables using 3-phase a.c. welding more than offset the advantages of the system. Our operators can do a consistently better job using the simpler d.c. welding heads.

Linde Air Products have done considerable research on 3-phase welding, and E. A. Clapp and N. G. Schreiner presented a paper on the subject to the American Welding Society in October 1951.

Mr. C. C. Hanke (in reply): The answer to Mr. Shaw's first question is that the first set of positioners was a big clamping beam. On the tilting tables it is simply clamped at one edge, because it did not have to rotate 360° but almost held itself on the table because of its weight and the friction between it and the table.

The author himself will have to reply to the second question.

I have little to add to Mr. Houldcroft's remarks on terms. I must confess I use the two words with the same meaning most of the time, and it will be interesting to clarify it. But it might be hard to decide on the differences.

I admit that our first manipulators were too awkward and costly. But it was the first job of its kind, and we were able to write off the cost of this equipment. It was suitable only for another vessel of the same size, but we did not have to make another.

The trunnion design was simple and was really built out of bits and pieces lifted from the junk yard of the works. It cost less than £2000, whereas the first one cost between £15,000 and £20,000. There was a considerable amount of engineering in the first, as it had to be perfectly balanced. To accommodate differences between building a 160-ft diameter sphere and a 120-ft dia. one we merely changed the contour plates on the bed of the manipulator.

The discussion on the remaining papers presented at the Autumn Meeting will be published in following issues of the Journal.

Welding
TECHNOLOGY

Welding and the Draughtsman

By H. B. Merriman, M.I.MECH.E., A.C.T. (BIRM.)

Some comparisons are made between the various stresses that arise in basic weld forms, and examples of simple calculations are given. A design procedure is outlined for instances when welds are subjected to combinations of static and dynamic loading.

Since much of the advice in the paper is drawn from experience in the design of pressure vessels some observations are given on the design of joints between ferritic and austenitic materials. The basic concepts are, however, applicable to most types of welded construction.

SINCE the necessary close association between the designer, metallurgist, welding engineer, and fabricating shop will be well-known, no attempt has been made in this paper to comment on this vital aspect, and the observations are devoted to the design of welded joints.

Most of the material is drawn from experience in the design of pressure vessels, but the substance is equally applicable to design for general welded fabrication. The theme generally considered is that of 'designing-out' objectionable features in welds and, where possible of 'designing-in' resilience or flexibility to the structure to preserve the welds from shock loads.

Stress Concentrations

The stress-raisers introduced by abrupt changes in cross-section or local discontinuity are, at the least, undesirable from the designer's viewpoint, and whilst they may not be serious in statically loaded joints in ductile metals not subjected to shock loading, they become dangerous in brittle metals (or ductile steels at a service temperature below their ductile-to-brittle transition point), and in joints subjected to cyclic loading.

Welds are frequently stress-raisers by virtue of the configuration of the plates to be joined, and because of their own contours: (the paper is concerned primarily with geometrical stress-raisers and not 'metallurgical' ones).

In statically loaded structures, the ductility of the material will allow yielding to take place and a redistribution and more uniform spreading of the stress. The catastrophic brittle fracture of fatigued metal or of carbon steel below its transition temperature is often initiated in a weld—at some flaw such as an arc crater or undercut—and whilst the fracture does not propagate along a weld (as far as is known from the literature) it is significant to note that its origin is often a weld. Brittle fracture in pressure-vessel carbon steels, although associated with 'low' temperature, has been known to occur during the testing of a vessel on a cold but not necessarily freezing day.

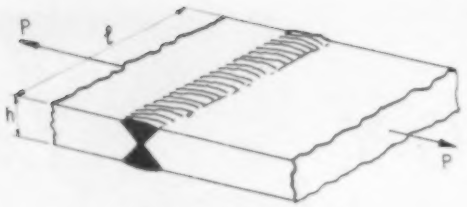
Weld contour is most important for weldments in cyclic service; a common instance of this is the skirt-to-shell attachment weld of a vertical pressure vessel subjected to cyclic thermal loads, variable wind loads, and vibrations transmitted to it from process flow variations.

Stresses in Butt Welds

The stress in a full-penetration butt weld uniting plates of equal thickness h (Fig. 1) is:

$$f_t = \frac{P}{hl} \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Paper presented to the North and South London Branches of the Institute of Welding in February and March 1959.



1—*Full penetration butt weld*

where f_t = tensile stress, lb/sq.in.
P = load, lb
l = length of weld, in.
h = thickness, in.

The weld reinforcement is not included in the computation.

The American Welding Society has reported[1] that butt welds are able to take pulsating compression stress from zero to maximum to above the yield for as many as 2×10^6 cycles. The conclusion is drawn that unless there is a reversal of stress, compression members designed by conventional methods are not subject to fatigue. Under tensile stressing, similar specimens have shown a fatigue strength above the yield when stressed in a range of $\frac{1}{2}$ max. to max. stress (for 2×10^6 cycles). Transverse butt welds with the reinforcements ground off have given the same fatigue strengths as the parent plate with the millscale left on. A value often taken for the stress concentration at the edge of a butt weld (not ground flush with parent plate) is 1·2.[2]

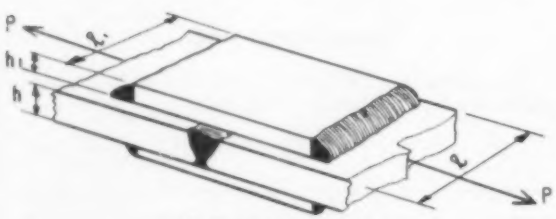
It is considered that the fatigue strength of a fully penetrated butt weld cannot be improved by adding reinforcing plates. Fillet welded butt straps reduce the fatigue strength by introducing stress concentrations, which result in failure of the *base* metal at stresses noticeably lower than the fatigue strength of the unreinforced joint. Butt straps are sometimes used in static loading (Fig. 2), and the customary formulae for calculating the stress in the welds is:

$$\text{Stress in fillet welds (lb/sq.in.)} = \frac{p}{0{\cdot}707h_1l_1} \quad \ldots\ldots\ldots\ldots (2)$$

$$\text{Stress in butt welds (lb/sq.in.)} = \frac{P}{(2h_1l_1+hl)} \quad \ldots\ldots\ldots\ldots (3)$$

where p = load in each butt strap (lb)
$= P\times\dfrac{\text{cross section of one strap}}{\text{total cross sectional area}}$
P = tensile load (lb)
h_1, l_1, h, l = dimensions from Fig. 2 (in.)

It is assumed in these formulae that the load P is distributed over the three plates in proportion to their cross sectional areas, about which there could be some doubt.

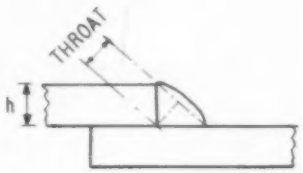


2—*Strapped butt weld*

A comparison of stresses for the two examples considered is given in Table I, taken from results published by Pemberton.[3] This author has also given the information reproduced in Table II.

Fillet Welds

Calculations for fillet welds are based on the assumption (confirmed by photoelastic tests) that the stress in the throat of a transverse fillet weld (Fig. 3) is principally tensile. The thickness of the throat for calculation purposes is taken as 0·707h.



3—*Fillet weld throat*

Table I

Direct fatigue tensile stresses for mild steel
(2×10^6 cycles)

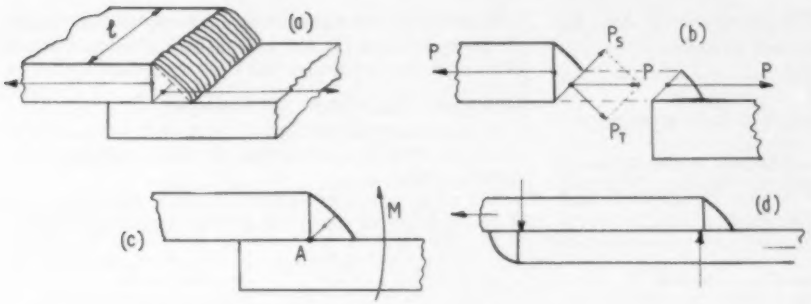
Test Piece	*Mean Stress 25,500: Limiting range of stress lb/sq.in.*	%	*Stress Concentration Factor K*
1. Unwelded bar	11,400	100	1·0
2. Single-V butt weld	6,400	56	1·8
Double-V butt weld	5,700	50	2·0
3. Single-V butt weld with reinforcement serrated	6,400	56	1·8
4. Single-V butt weld with transverse fillet-welded butt straps	4,200	37	2·7
5. Similar model to (4) machined from solid metal	5,700	50	2·0
6. Transverse fillet weld symmetrical	2,100	19	5·2
7. Longitudinal fillet welds	1,800	15	6·6

Table II

Fatigue limits for butt welds in mild steel

Test Piece	*Stress under pre-load lb/sq.in.*	*Stress under load, lb/sq.in.*	*Authority*
1. Unwelded bar	+25,800	±11,400	Thurn
2. Single-V butt weld	0	±12,300	Haigh
	+13,400	± 9,000	Haigh
	+25,800	± 6,500	Haigh
	− 6,720	±17,900	Haigh
	−11,200	±13,400	Haigh
	+13,400	±18,300*	Haigh
3. Double-V butt weld	+25,800	± 5,600	Thurn
4. Single-V butt weld with transverse fillet-welded butt straps	+25,800	± 4,500	Thurn

* Stress relieved



4—*Loading on fillet welds*

Reasoning on similar lines, it is seen that the weakest part of this connection is the narrow throat which must transmit the full load P as well as resist the bending moment that is thereby imposed (Fig. 4*a*). If the complete load is assumed to be uniformly spread over the throat area as a tensile stress normal to the throat cross-section, that stress would be:

$$f_t = \frac{P}{0{\cdot}707hl} = \frac{1{\cdot}414P}{hl} \quad \ldots\ldots\ldots\ldots (4)$$

This is a rough and ready formula, and its applicability will be demonstrated later.

Replacing P by its two components P_T and P_S normal and parallel to the throat cross section (Fig. 4*b*), tensile and shear loads respectively, and each equal to $0{\cdot}707P$, give

(i) A tensile stress normal to the weld throat:

$$f_{th} = \frac{0{\cdot}707P}{0{\cdot}707hl} = \frac{P}{hl} \quad \ldots\ldots\ldots\ldots (5a)$$

and (ii) A shear stress on weld throat:

$$f_s = \frac{0{\cdot}707P}{0{\cdot}707hl} = \frac{P}{hl} \quad \ldots\ldots\ldots\ldots (5b)$$

The stress in the weld throat due to bending (Fig. 4*c*) is:

$$f_b = \frac{M}{Z_{\text{throat}}}$$

Where M is the bending moment $= P \cdot \frac{h}{4}$

and Z_{throat} is the section modulus $= \frac{l(0{\cdot}707h)^2}{6}$

so that

$$f_b = \frac{6Ph}{4l(0{\cdot}707h)^2} = \frac{3P}{hl} \quad \ldots\ldots\ldots\ldots (5c)$$

At the point A in Fig. 4*c* the normal tensile stress and the tensile stress due to bending are additive and become:

$$f_{tot} = \text{eq.5a} + \text{eq.5c} = \frac{P}{hl} + \frac{3P}{hl} = \frac{4P}{hl} \quad \ldots\ldots\ldots (5a)$$

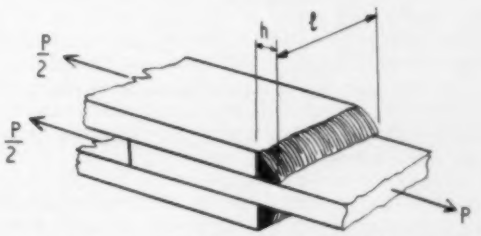
Combining this total tensile stress with the shear stress to find the maximum principal stress gives:

$$f_{max.} = \tfrac{1}{2}\left\{\frac{4P}{hl} + \sqrt{\left[\left(\frac{4P}{hl}\right)^2 + 4\left(\frac{P}{hl}\right)^2\right]}\right\} = \frac{4{\cdot}24P}{hl} \quad \ldots. (5)$$

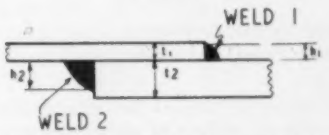
If the weld were preserved from bending stresses, the combination of normal tensile and shear on the weld throat would give a principal stress:

$$f_{max.} = \tfrac{1}{2}\left\{\frac{P}{hl} + \sqrt{\left[\left(\frac{P}{hl}\right)^2 + 4\left(\frac{P}{hl}\right)^2\right]}\right\} = \frac{1{\cdot}618P}{hl} \quad \ldots. (6)$$

In practice, every attempt is made to eliminate the bending stresses, usually by adding another weld (Fig. 4*d*), and a combination of plate stiffness and overlap allows the reactions P_R to be small enough to have negligible effect upon weld stressing.



5—*Symmetrical transverse fillet welds*



6—*Lap joint between plates of unequal thickness*

In symmetrical transverse fillet welds (Fig. 5) the stress in each weld

$$f_t = \frac{P/2}{0{\cdot}707hl} = \frac{0{\cdot}707P}{hl} \quad \ldots\ldots\ldots\ldots (7)$$

When the fillet welds unite a lap joint composed of plates of unequal thicknesses (Fig. 6), the loads carried by each plate depend on the ratio of the plate thickness. For example:

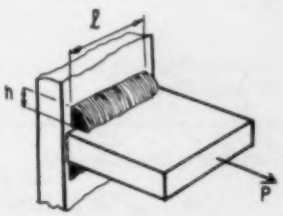
Stress in weld 1, $f_1 = \frac{1{\cdot}414Pt_1}{lh_1(t_1+t_2)}$ $\ldots\ldots\ldots\ldots (8)$

Stress in weld 2, $f_2 = \frac{1{\cdot}414Pt_2}{lh_2(t_1+t_2)}$ $\ldots\ldots\ldots\ldots (9)$

When the weld leg is the same as the plate thickness (which is not always practicable):

$$f_1 = \frac{1{\cdot}414P}{l(t_1+t_2)} \text{ and } f_2 = \frac{1{\cdot}414P}{l(t_1+t_2)}$$

This is a rather uncertain analysis when the top plate is relatively thin compared with the bottom plate. If the top plate is visualized as a piece of rubber, it is seen that weld 2 takes almost the whole of the load.



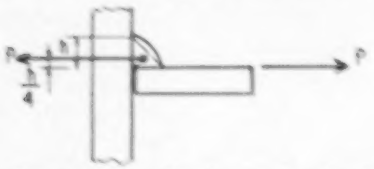
7—*Transverse fillet welds under tension*

When the plates and welds are of equal size, the stress in each weld

$$f_s = \frac{0{\cdot}707P}{hl} \quad \ldots\ldots (10)$$

This formula applies also to the weld arrangement shown in Fig. 7.

Should one weld be omitted in Fig. 7, the joint will be subjected to bending (Fig. 8). Assuming P (for



8—*Transverse fillet weld under tension and bending*

convenience) acts along the fusion line, the direct tensile stress will be:

$$f_a = \frac{1{\cdot}414P}{hl} \quad \ldots\ldots (11)$$

and tensile stress due to bending

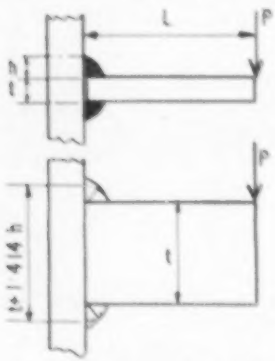
$$f_t = \frac{M}{Z} = \frac{6M}{(0{\cdot}707h)^2 l} = \frac{3P}{hl} \quad \ldots\ldots (12)$$

Adding these tensile stresses

$$f_a + f_t = \frac{4{\cdot}414P}{hl} \quad \ldots\ldots (13)$$

which is 3·1 times as large as the symmetrical arrangement (ignoring the effects of shear stresses).

The analysis of stresses in fillet welds resisting a bending moment, as shown in Fig. 9, is dependent upon the ratio of h to t. Usually t is greater than $2h$,



9—*Fillet welds resisting bending moments*

but when it is less, the bending stress f_b is developed from bending moment and section modulus:

$$f_b = \frac{6PL\,(t + 1{\cdot}414h)}{1{\cdot}414lh\,(3t^2 + 2h^2 + 4{\cdot}24th)} \quad \ldots\ldots (14)$$

Where t is greater than $2h$, f_b simplifies to

$$\frac{1{\cdot}414PL}{lth} \quad \ldots\ldots (15)$$

Allowing for each weld to take $\frac{1}{2}P$, the tensile stress in the weld throat

$$f_t = \frac{0{\cdot}707P}{lh} \quad \ldots\ldots (16)$$

Combining these stresses

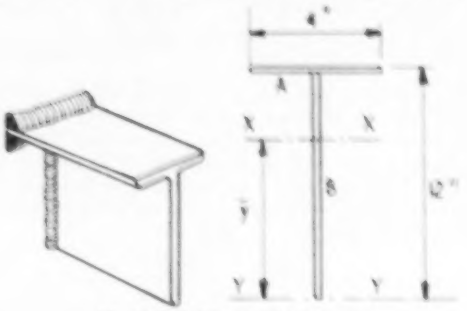
$$f_{max.} = \sqrt{(f_b^2 + f_t^2)} = \frac{0{\cdot}707P}{lh}\sqrt{\left(1 + \frac{4L^2}{t^2}\right)} \quad \ldots (17)$$

Sketches of the alternative methods of attachment are given in Table III, for comparison of the calculated stresses in the weld, and the size of the weldment.

Calculation of fillet welds for attaching beams

A convenient method of computing the size of fillet welds to attach a cantilever is to calculate a line section modulus.

The welds are represented by single bars (Fig. 10) of one unit width, and their section modulus is found.



10—*Calculation of weld moments*

Flange welds are treated as one single bar, unless they are spaced quite some distance apart. Dividing the bending moment by this line section modulus will give a *load* in the welds per inch run; from this can be established a weld of suitable size.

Element	*Area A, sq.in.*	*Distance y from YY, in.*	*Ay*	*Ay²*	*Moment of Inertia about N.A. I_{XX}*	*Moment of Inertia about YY $I_{YY} = I_{XX} + Ay^2$*
A	4	12	48	576	4·12	576·3
B	12	6	72	432	144	576
A + B	16	—	120	—	—	1152·3

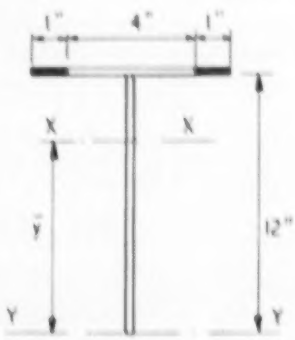
$\bar{y} = 120/16 = 7\frac{1}{2}$ in.

$I_{XX} = I_{YY} - Ay^2 = 1152{\cdot}3 - (16 \times 7\frac{1}{2}^2)$

$= 252$ in.^{4}

Considering the welds on the flange (element A), their distance from the neutral axis (XX) is 12–7½ in. = 4½ in., and the line section modulus becomes 252/4½. This value of Z_{line} may be inserted in the formula F(lb/in.) = M/Z, and the load per inch run of the weld determined.

The size of the weld will be influenced by the thickness of the flange and web and also by the member to which the beam is to be attached. This may seem obvious, but perhaps what is not so apparent is the advantage of calculating the moment of inertia of the



11—*Calculation of weld moments*

welds in the seemingly laborious manner shown. This method allows for additions; $\bar{y}$ can be adjusted accordingly, and as a 'running plot' is kept of I_{YY}, the moment of inertia can be found for each addition of weld that is made. To illustrate this, take a cantilever, as shown in Fig. 10 to support a load of $1\frac{1}{2}$ tons concentrated at 8 ft 0 in. from the welds.

$$M = 2240 \times 1\tfrac{1}{2} \times 8 \times 12 = 320{,}00 \text{ in.lb}$$

Assume that the allowable stress in the weld is 14,000 lb/sq.in. and that a weld greater than $\frac{1}{2}$ in. leg length is, in this case, impracticable.

$$\text{Permissible load per inch of weld} = 14{,}000 \times \tfrac{1}{2} \times \frac{1}{1{\cdot}62}$$

$$= 4350 \text{ lb.}$$

$$\text{Actual load in weld} = \frac{M}{Z} = \frac{320{,}000}{56} = 5710 \text{ lb/in.}$$

(unacceptable)

Consider increasing the flange to 6 in. wide; add 1 in. on either side of the flange (Fig. 11) directly into the calculation:

Element	*A*	*y*	*Ay*	*Ay²*	I_{NA}	I_{YY}
A+B	16		120			1152·3
C	2	12	24	288	2/12	288
(A+B)+C	18		144			1440·3

$$\bar{y} = \frac{144}{18} = 8$$

$$I_{XX} = 1440 - (18 \times 8^2) = 388$$

$$Z = \frac{388}{(12-8)} = 97$$

and $F = \dfrac{320{,}000}{97} = 3300$ lb/in., which could be acceptable.

Design for Fatigue Loads

Concentration factors (multiples of the calculated static stress) determined experimentally enable a suitable size of a weldment for fatigue-type loading to be derived. Typical values are shown in Table IV.

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Type of Joint	*Factor K*	*Authority*
At edge of reinforced butt weld	1·2	Jennings[3]
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Referring to the values for stress concentrations given in Table I, it will be noted that a high mean static stress acting before and during the variable stress has an important bearing on the stress concentration factor.

A method suggested by Koopman[5] for evaluating design stresses under conditions where a fluctuating load is superimposed upon a constant load is shown in Fig. 12. Values for the steady stress are set along the abscissa—ultimate or yield stresses divided by a factor of safety determine the maximum design stress for static loading. The ordinate is graduated in design stresses for fluctuating loads up to the acceptable endurance limit.

The line *DE* being parallel to line *AB* (or *AC*), the equation to the line *DE* (the *Design Line*) can be written:

$$\frac{K \cdot f_v}{f_{vA}} + \frac{f_c}{f_{cA}} = 1 \quad \ldots\ldots\ldots\ldots\ldots (18)$$

where: $K \cdot f_v$ = stress concentration factor multiplied by the variable stress
f_{vA} = allowed or design stress for variable loads
f_c = constant or steady stress
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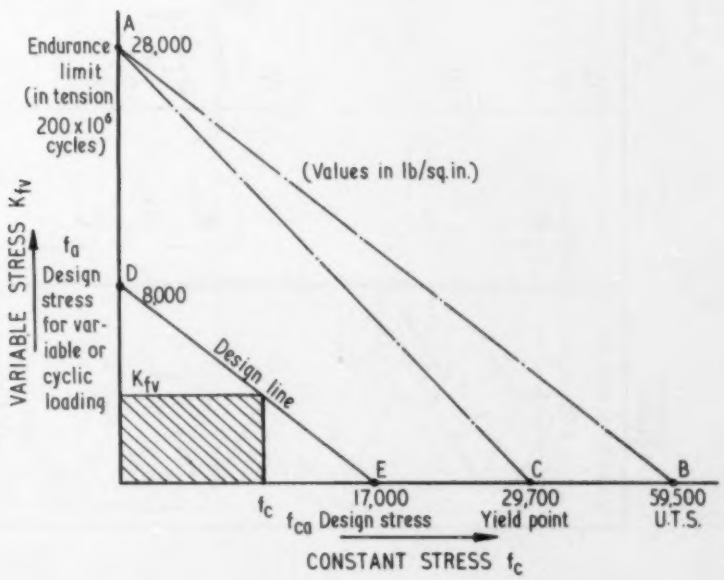

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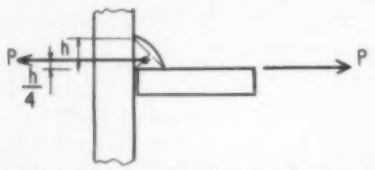

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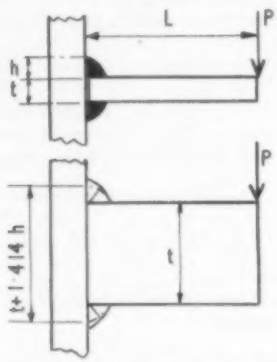

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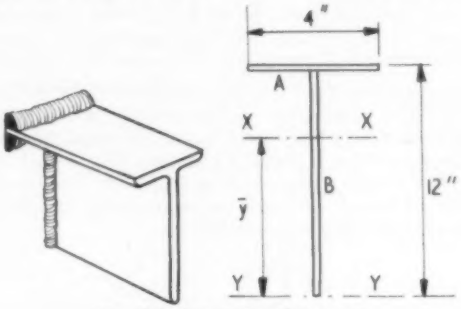

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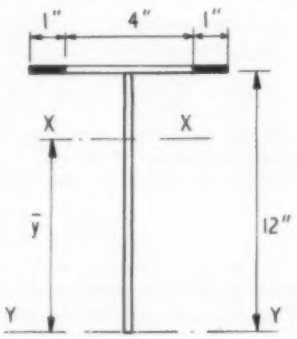

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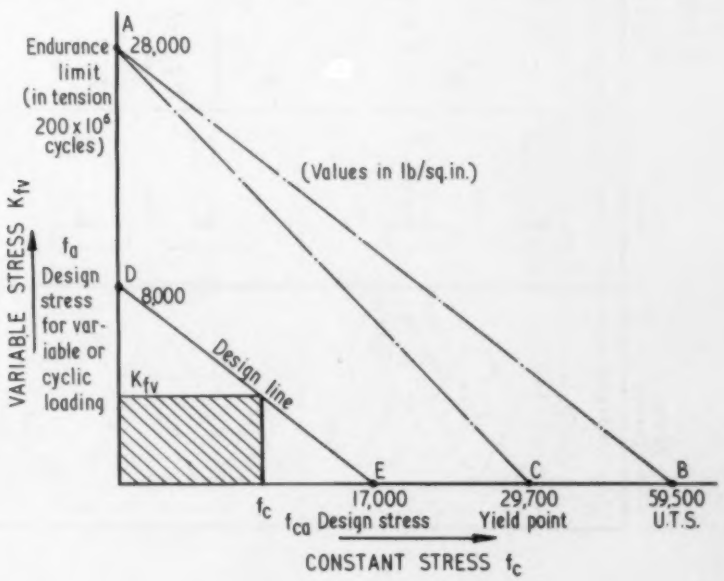
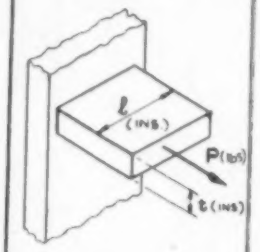
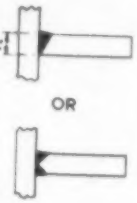
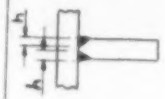
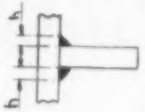
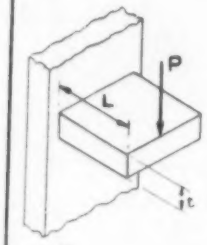
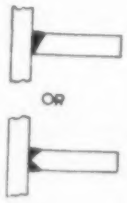
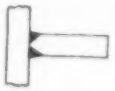
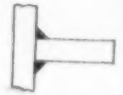
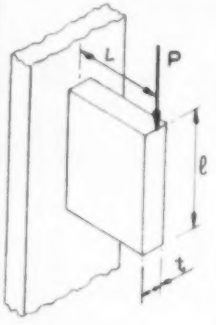
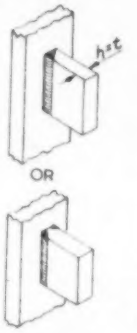
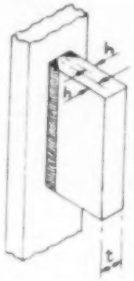
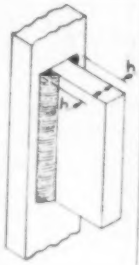
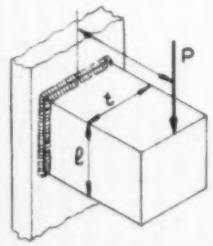
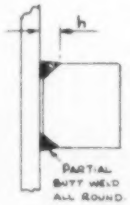
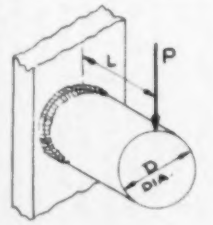
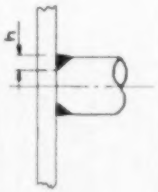
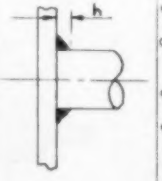
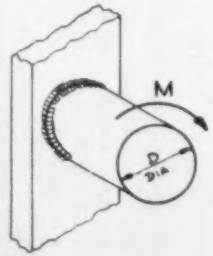
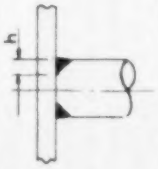
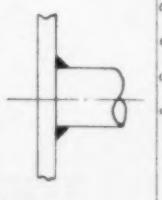


12—*Method of evaluating design stresses for fluctuating loads*

Table III

Weld stresses and sizes for some commonly used attachments

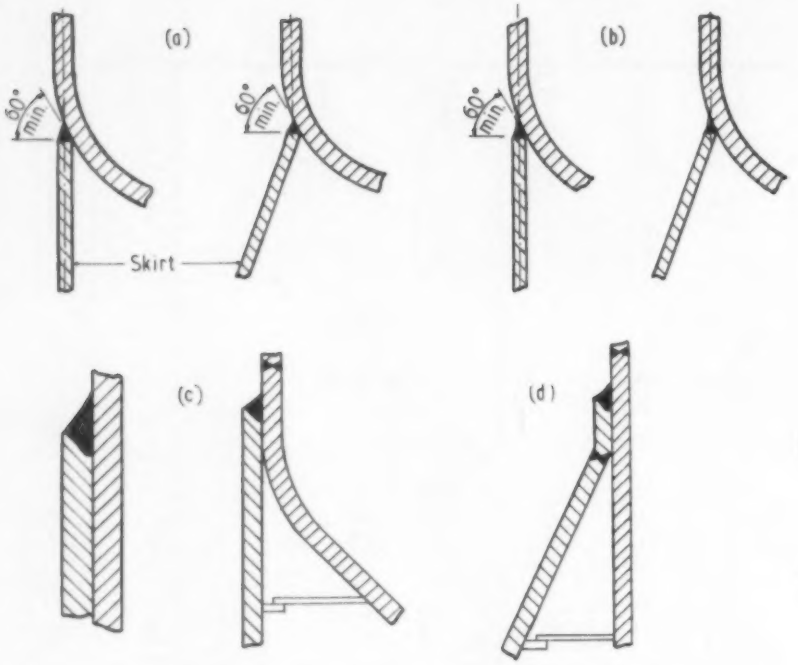
Method of Loading	*Type of Joint*	1. *Stress in Weld* f 2. *Weld Size* h	*Type of Joint*	1. *Stress in Weld* f 2. *Weld Size* h	*Type of Joint*	1. *Stress in Weld* f 2. *Weld Size* h
		① $f = \frac{P}{lh}$ ② $h = \frac{P}{lf}$		① $f = \frac{3P}{lh}$ ② $h = \frac{.5P}{lf}$		① $f = \frac{.707P}{lh}$ ② $h = \frac{.707P}{fl}$
		① (BENDING) $f = \frac{6PL}{lh^2}$ (a) (SHEAR) AT MID DEPTH $f = \frac{3}{2}\frac{P}{lh}$ ② $h = \sqrt{\frac{6PL}{lf}}$		① (a) (BENDING) $f = \frac{3PLt}{h(3t^2-6lh+4h^2)}$ (SHEAR) $f = \frac{3}{4}\frac{P}{lh}$		① (BENDING) $f = \frac{1.414\,PL}{lth}$ (a) $f_{max} = \frac{.707P}{lh}\sqrt{1+\frac{4l^2}{t^2}}$ (BENDING & SHEAR) WHEN h IS SMALL COMPARED WITH t. ② $h = \frac{1.414\,PL}{flt}$
		① (BENDING) $f = \frac{6PL}{l^2h}$ (a) (SHEAR) AT MID DEPTH $f = \frac{3}{2}\frac{P}{lh}$ ② $h = \sqrt{\frac{6PL}{l^2f}}$		① (BENDING) $f = \frac{3PL}{l^2h}$ (a) (SHEAR) AT MID DEPTH $f = \frac{3}{4}\frac{P}{lh}$		① (BENDING) $f = \frac{4.24\,PL}{l^2h}$ (a) (SHEAR) AT MID DEPTH $f = \frac{1.06\,P}{lh}$ ② (BENDING) $h = \frac{4.24\,PL}{l^2f}$ (SHEAR) $h = \frac{1.06\,P}{lf}$

				① (a) $f = \frac{6PL\ell}{\ell^3 t - (\ell - 2h)^3(t - 2h)}$ IF h IS SMALL COMPARED TO ℓ AND HIGHER POWERS THAN THE FIRST OF ℓ MAY BE NEGLECTED, THE VALUE OF f REDUCES TO - $\frac{3PL}{\ell h(3t + \ell)}$ ② $h = \frac{3PL}{f\ell(3t + \ell)}$		① $f = \frac{4{\cdot}24\,PL}{\ell h(3t + \ell)}$ ② $h = \frac{4{\cdot}24\,PL}{f\ell(3t + \ell)}$
				① $f = \frac{10{\cdot}2\,PLD}{(\text{BENDING})\ D^4 - (D - 2h)^4}$ IF h/D IS SMALL $f \simeq \frac{1{\cdot}27\,PL}{D^3 h}$ ② $h = \frac{1{\cdot}27\,PL}{fD^2}$		① (a) $f = \frac{10{\cdot}2\,PL(D + 1{\cdot}414h)}{(\text{BENDING})\ (D + 1{\cdot}414h)^4 - D^4}$ (a) $f \simeq \frac{1{\cdot}76\,PL}{(\text{BENDING})\ h(D + {\cdot}707h)^2}$ ② $h = \frac{1{\cdot}76\,PL}{f(D + {\cdot}707h)^2}$
				① (a) $f = \frac{5{\cdot}1M(D - h)}{(\text{SHEAR})\ D - (D - h)}$ $f \simeq \frac{{\cdot}9M}{(\text{SHEAR})\ D^4(D - h)^4}$		① (a) $f = \frac{5{\cdot}1M(d + 1{\cdot}414h)}{(\text{SHEAR})\ (d + 1{\cdot}414h)^4 + d^4}$ (a) $f \simeq \frac{{\cdot}9M}{(\text{SHEAR})\ hD^2}$ ASSUMING THAT THE TORQUE M IS RESISTED BY A SHEAR FORCE ACTING IN WELD THROAT

Maximum stress from bending occurs at extreme upper edge of weld. Shear stress at this point is zero.

* Maximum shear stress occurs at mid-depth, and is 1½ times the mean shear stress.

[a] See references.



13—*Junctions between pressure vessel and skirt*

eliminate divisors, there seems to be little to be gained from this. An example is given of the determination of the length l of a butt weld joining two plates 1 in. thick, and carrying a constant load of 10,000 lb (tensile) plus a load variation up to 40,000 lb (tensile).

$$K = 1{\cdot}2 \text{ (Table IV)}$$

Variable stress

$$f_v = \frac{\frac{1}{2}\text{ (max. load} - \text{min. load)}}{\text{Area of weld}} = \frac{\frac{1}{2}\text{ (40,000–10,000)}}{1 \times l} = \frac{15{,}000}{l}$$

Steady stress

$$f_c = \tfrac{1}{2}\text{ (max. load} + \text{min. load)} = \frac{\frac{1}{2}\text{ (40,000+10,000)}}{1 \times l} = \frac{25{,}000}{l}$$

$f_{vA} =$ 8,000 lb/sq.in.
$f_{cA} =$ 17,000 lb/sq.in.

Substituting in equation 18:

$$\frac{1{\cdot}2 \times 15{,}000}{l \times 8{,}000} + \frac{25{,}000}{l \times 17{,}000} = 1$$

$$l = 2{\cdot}25 + 1{\cdot}47 = 3{\cdot}72 \text{ in.}$$

(if designed for static loading only

$$l = \frac{40{,}000}{17{,}000} = 2{\cdot}35 \text{ in.)}$$

If the loading were cyclic over the range $\pm 40{,}000$, the weld length l would become:

Variable stress $f_v = \frac{\frac{1}{2}\text{ (40,000} - (-\text{ 40,000))}}{1 \times l} = \frac{40{,}000}{l}$

Steady stress $f_c = 0$ (in this example)

Substituting in equation 18:

$$\frac{1{\cdot}2 \times 40{,}000}{l \times 8{,}000} + 0 = 1$$

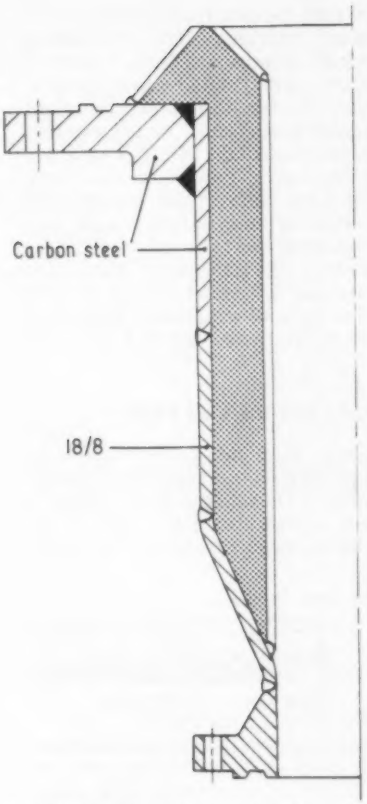
Whence $l = 6$.

An interesting joint connection (which to some extent defies classification into fillet or butt) is the junction between a vertical pressure vessel and its skirt. For medium temperature service the non-cyclic loading the joint in Fig. 13*a* is frequently used. The fatigue strength is increased if the weld is faired, as shown in Fig. 13*b*, to eliminate notch effect. For more severe conditions of both thermal and mechanical cyclic stressing, the detail shown in Fig. 13*c*, or for a tapered skirt, Fig. 13*d*, is selected.

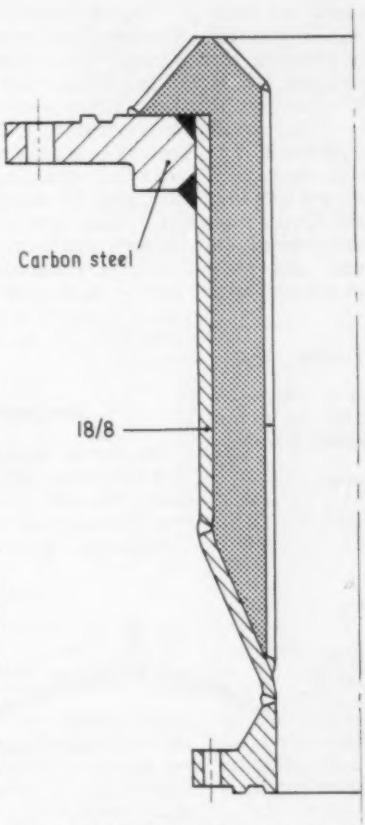
Stainless Steel to Carbon Steel Welds

A good, sound, full strength joint can be made between the frequently used Cr–Ni austenitic stainless steels and plain carbon steel (with carbon up to about 0·3%) or low-alloy weldable steels. It is assumed that the corrosion aspects to this junction are acceptable: for joints in contact with water, or oxidizing acid solutions, the carbon steel becomes the sacrificial metal and a corrosion allowance must be added to the plate thickness.

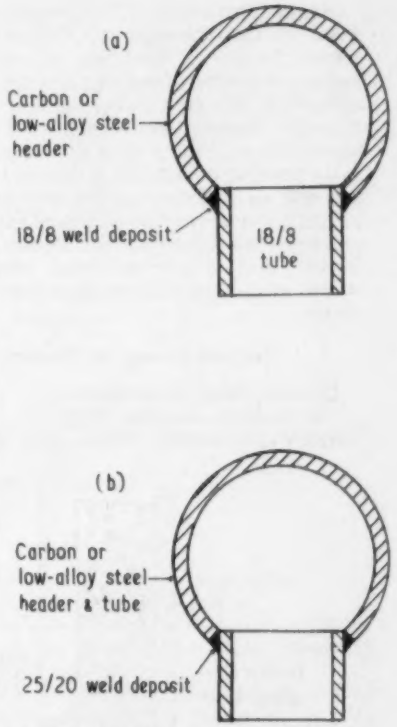
Where possible, the junction should be placed to take advantage of the elastic and plastic yielding of both metals. This is exemplified in Fig. 14 where an 18/8 outlet flange is provided to a carbon molybdenum steel vessel—a stub attached to the flange and a similar one to the vessel (by extending the nozzle stand-out) enables this desiderata to be attained. To make this junction by providing a 16 in. o.d. pipe to be welded into the 400 lb flange (Fig. 15) is to be avoided, for thermal stressing due to differential expansion leads to cracking in the weld. Likewise, an arrangement shown in Fig. 16, which has no resilience designed into it, is most undesirable in any thermal cycling conditions. Figure 16*a* shows an 18/8 pipe



14—*Method of attaching 18/8 outlet flange to low-alloy vessel*



15—*As Fig 14, but showing undesirable connection of 18/8 pipe direct to flange*



16—*Tube to header connections:* (a) *Undesirable;* (b) *preferred use of high-alloy weld deposit*

welded into a ferritic steel header; Fig. 16*b* depicts a low-alloy (say 5% Cr–½% Mo) steel tube welded into a header of similar material, with a 25/20 electrode, the differential expansion in the weld itself being undesirable.

Stainless (18/8) steel has a coefficient of expansion of about $10{\cdot}4\times10^{-6}$ per °F., whilst carbon steel and low-chrome ferritic steels have a coefficient of 8×10^{-6} A butt joint between pipes of equal thickness develops a hoop stress f at the junction:

$$f = \tfrac{1}{2}E(T_2-T_1)\ (\alpha_{18/8}-\alpha_{cs}) \qquad \ldots\ldots\ldots (19)$$

where E = Young's Modulus, which can be assumed identical for both metals (say 29×10^6 lb/sq.in.)

(T_2-T_1) = Overall temperature change, °F.

$(\alpha_{18/8}-\alpha_{cs})$ = The difference in the coefficients of expansion (per °F.)

If such a joint were raised in service from 50° to 1000°F.:

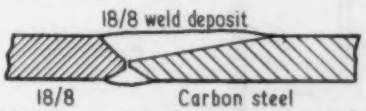
$$f = \tfrac{1}{2}\times29\times10^6\times950\times2{\cdot}4 = 33{,}000 \text{ lb/sq.in.}$$

which would be compressive in the 18/8 and tensile in the ferritic material.

Connecting the austenitic pipe directly into the shell, as, say, in Fig. 16, would force almost all the differential strain into the austenitic tube. This would increase the maximum stress by a factor of approximately 3·6 as compared with the single butt weld.

The weld uniting the stainless steel to the carbon steel is likely to suffer the deleterious effects of carbon migration from the carbon steel into the 18/8, at the carbon steel end of the junction. At this point, the weld may become embrittled and sensitized to intergrannular corrosion. Since it is most desirable that this weld should be ductile, a ferrite content of between 3 and 8% is considered desirable; electrodes of the 18/8 type are available to provide the requisite amount of ferrite. Deposits from 25% Cr–20% Ni electrodes have been used extensively in the U.S.A. for this type of junction, there being ample chromium to allow for its depletion by migrating carbon, and the nickel confers the requisite ductibility to the weldment.

Historically, the stainless/carbon-steel junction in pipework has been interesting. One solution to the problem was to use a transition piece, with 18/8 at one end and the composition gradually changing over the length to terminate in a carbon steel matching to the pipework. The superposition of internal pressure loading and axial loading has reduced the hot-fatigue life of specimens held at a constant temperature, but an improved performance has been obtained by altering the weld preparation on the ferritic side (*see* Fig. 17).

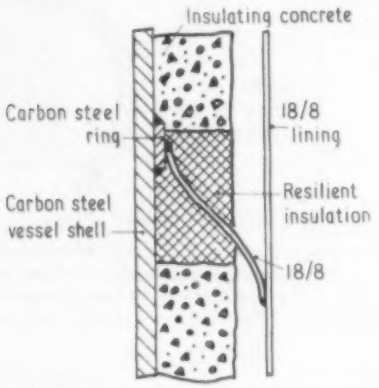


17—*Suitable connection for 18/8 to carbon steel pipes*

At the ferritic end of this junction there is a likelihood of carbon migration, which has a two-fold effect: the carbon steel near the weld interface will suffer a depletion of carbon; and the 18/8 weld will be affected by the undesirable permeation of carbon. In the weld deposit there is a possibility of the brittle sigma phase forming near the ferritic interface. The juxta-position of material in the weld and interfaces of material of differing crystal structure and physical properties creates a 'metallurgical notch'. Under most corroding conditions that are usually encountered, the ferritic steel is the sacrificial element, and local strains induced by welding can accelerate this corrosive attack.

Internal Linings to Pressure Vessels

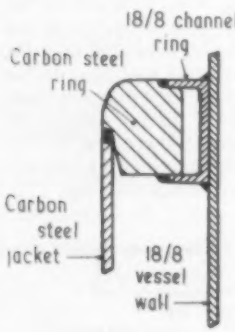
Internal linings to pressure vessels can be supported on a resilient member (Fig. 18). The connecting member is invariably stainless steel so that it may be



18—*Resilient support for 18/8 lining to pressure vessel*

made as thin as possible (no corrosion allowance is needed). The junction with the vessel shell can be conveniently made to a ring connected to the shell; the inherent plasticity of 18/8 gives the often indeterminate yielding that may be required, and a stainless/stainless weld can be made in the corrosion, or hot, zone.

A frequently encountered junction is that of a hot water or steam jacket being attached to a stainless steel vessel. A well-proven connection is illustrated in Fig. 19, where the 18/8 attachment provides a resilient or yielding connection.

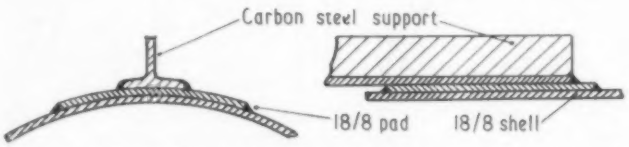


19—*Junction of steam jacket to stainless steel vessel*

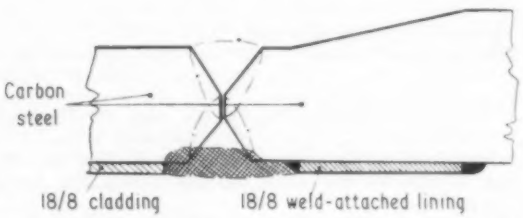
The 18/8 steels are used for two dissimilar purposes: for their high or low temperature (−50°F. and below) strength and absence of a transition from ductile to brittle failure; and for their corrosion resisting properties. When used for the latter purpose, junctions between them and carbon steel must be arranged so that there is no contamination of the 18/8. For supports and strengthening members this is conveniently arranged by attaching the carbon steel members to 18/8 pads (where weld contamination would not matter) and then attaching the 18/8 pad to the 18/8 vessel or container (Fig. 20). Experience shows that carbon steel supports can be welded directly to 18/8 of 10 s.w.g. or thicker without weld decay sensitizing effects on the inside of the vessel: an 18/8 electrode is used.

Junctions of Lined and Clad Plates

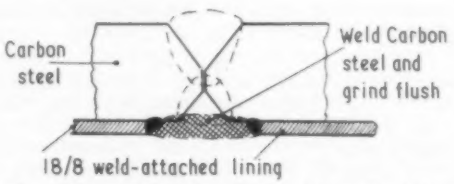
A typical method of shop fabrication of ferritic steel pressure vessel plates having stainless steel linings weld-attached, or clad, is shown in Fig. 21. When a weld-attached lined or a clad plate joins with an unlined plate, a corrosion allowance may be added to the



20—*Attachment of supports through pads to stainless steel vessel*



21—*Suitable joint between carbon steel plates with 18/8 weld-attached lining*

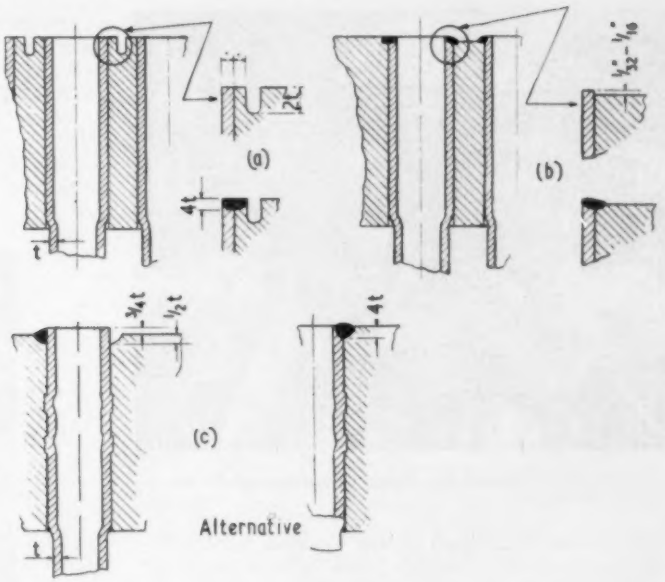


22—*Protection of transition from lined to unlined plate*

unlined plate, thus making the unprotected plate thicker than the lined or clad one. The tapered transition portion should be protected as shown in Fig. 22.

Welding of Tube to Tube Sheet

Of the methods that may be used for this purpose one must be selected which eliminates the need for post-heat treatment of the whole tube bundle, so as to



23—*Tube joints:* (a) *For argonarc welding;* (b) *alternative method;* (c) *metal-arc seal weld on expanded joint*

avoid distortion of the tube sheet. This dictates the use of 18% Cr–8% Ni or 25% Cr–20% Ni electrodes for steels which would require post-heat treatment if a matching electrode were used.

The materials to be joined fall into two groups; those which can be welded by argonarc and those which can be metalarc welded. Argonarc welding is suitable for 18/8, aluminium bronze, and killed carbon steels; metalarc welding is customarily used for unkilled plain carbon steels and for C–½% Mo, 1% Cr–½% Mo, and 4/6% Cr–½ Mo steels.

Figure 23*a* illustrates the weldment, used for argonarc welding (without the addition of filler wire) and has been used for joining 18/8/1, aluminium bronze (ASTM 171 Alloys *D* and *E*), and killed carbon steels. This preparation presents a desirable arrangement in that two equal thicknesses are presented for welding. There is, too, in the 'neck' of the tube sheet preparation a measure of resilience. The tube is not expanded in the ordinary sense; there are no expansion grooves, but the tube is lightly expanded to affect a seal over the whole depth of the tube sheet to prevent the ingress of shell side fluid. This weld, having a throat thickness equal to that of the tube wall, is considered to be a full-strength weld.

An alternative to this method, which has been used for 18/8 and killed carbon steel, is shown in Fig. 23*b*. An advantage of these methods lies in the light expansions required, which avoids a full expansion of work-hardening materials such as 18/8.

The metalarc welding of tubes to tube sheets in plain carbon and low-alloy steels is not (at present) regarded in the same way as the full-strength welds just considered. Many techniques progress slowly, moving cautiously from one proven method to any innovation. This is so for carbon and low-alloy steels, where conservative users of exchangers prefer to adhere to the established practice of fully expanding the tubes into grooves (Fig. 23*c*). The weld preserved from end-thrusts due to tube bundle handling, serves only as a seal.

Matching electrodes are used for plain carbon steels, and 18/8 or 25/20 electrodes for 1% Cr–½ Mo, and 4/6% Cr–½ Mo steels.

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A corner of the Engineering, Marine, Welding, and Nuclear Energy Exhibition

THE WELDING EXHIBITION 1959

Some impressions of the novel features that were shown in the Welding Section of the Engineering, Marine, Welding, and Nuclear Energy Exhibition, held at Olympia from 16th to 30th April.

PERHAPS the most satisfying feature of the exhibition for the welding industry was that, although the exhibits showed, in general, that progress in the engineering and allied industries in the past 18 months had been more in the nature of a development of existing materials, machinery, and techniques rather than startling new discoveries, equipment in the welding section was largely new. Many were being shown or described for the first time, and some had been prepared only just in time to go on show.

In this brief review of only a few of the exhibits relating to welding it is convenient to divide them into broad groups.

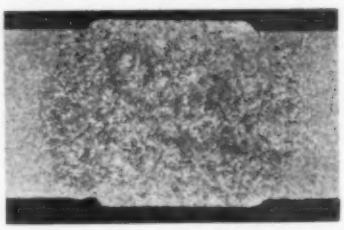
Arc Welding

Though manual electric arc welding is probably still the most widely used process, the most prominent and interesting displays in the welding section were of automatic equipment—in almost all the welding and allied processes.

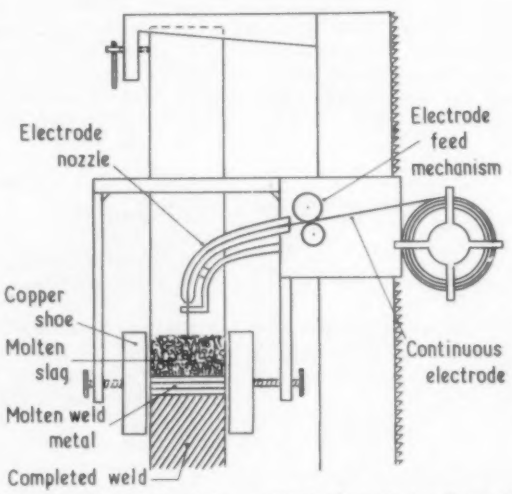
Since the development of the electro-slag welding process of welding in Russia there has been great interest in Britain in its application to the welding of thick plate, with startling economies in production times.

Quasi-Arc Ltd. have developed an entirely British machine which adapts the well-tried Unionmelt submerged-arc process for welding in the vertical position. As in the original Russian process, moveable copper dams support the molten weld metal, which is deposited from the normal type of Unionmelt electrode and flux composition. There is full automatic control, so that the welding head and dams are raised progressively as the weld is deposited. The resulting deposit, like that from the normal submerged-arc process, is sound and free from flaws, though it has a relatively coarse, cast structure.

The Vertomatic slag welding machine, now being made available in this country by Rockweld Ltd., is a development of the Czechoslovakian Vus process, and it has been given very exhaustive trials by the Company's Belgian colleagues Arcos. A demonstration on

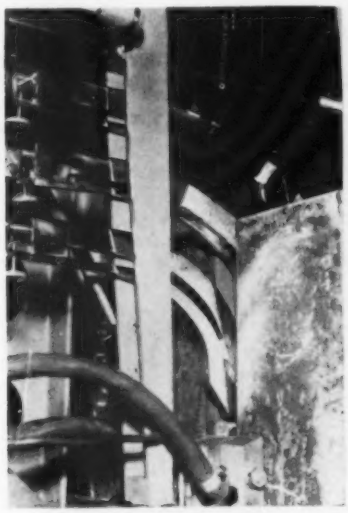


Cross-section of a weld made by the Rockweld Vertomatic machine



Principle of the Quasi-Arc method of vertical submerged arc welding

the stand showed that a vertical butt weld between two $2\frac{3}{4}$ in. thick plates 13 ft long would take only four hours to deposit; by manual welding it would take four operators about a week. The electrode wires are fed downwards through curved guides into a gap of about $1\frac{1}{8}$ in. between the two plates, and they are oscillated within the gap to distribute the deposit. Special composite electrodes can be used for making alloyed weld metals.



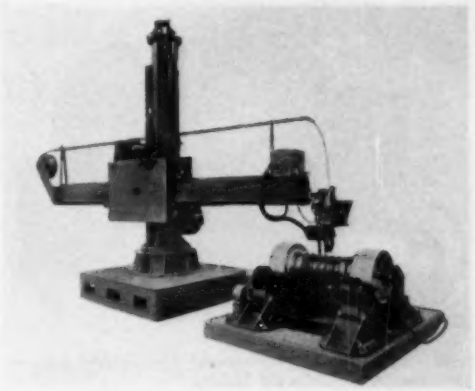
Plates being welded by the Rockweld Vertomatic machine

It is interesting to learn that a third machine, not shown at the Exhibition, is soon to be marketed in Britain by Welding Supplies Ltd.

When it is realised that butt welds in thick pressure vessels for nuclear power plant may take up to 12 hours per foot to complete by manual welding methods the potentialities of slag welding techniques are clear. Yet there must be a considerable amount of development work and research before these machines can be applied to high-class work where, for example, high notch ductility at low temperatures is vital. But it cannot be doubted that the process will find immediate application in heavy engineering fabrication and where high production rates are essential.

For the more normal structural work, with plate thicknesses of about $1\frac{1}{4}$ in. maximum, there is an increasing use of automatic and semi-automatic methods of welding where relatively long straight lengths of weld have to be deposited. In the shipbuilding industry in particular and in structural fabricating shops components have often to be joined by a double line of fillets—stiffeners to bulkhead panels or webs to plate girder flanges and so on.

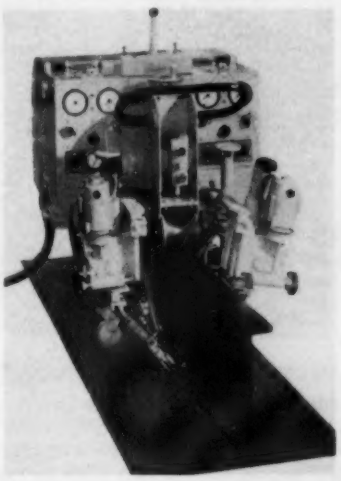
Machines for this purpose have been made by a number of equipment manufacturers. Murex Welding Processes Ltd. have mounted two of their Muramatic heads on a self-propelled carriage, so as to deposit simultaneously double h.v. fillets. Since the carriage speed is infinitely adjustable between 5 and 25 in./min. all sizes of weld can be made.



Lincoln L.R.C. travelling boom and revolving column, fitted with a Lincolnweld B.10 fully automatic submerged arc welding unit, working in conjunction with Lincoln L.S.A.R. rotators

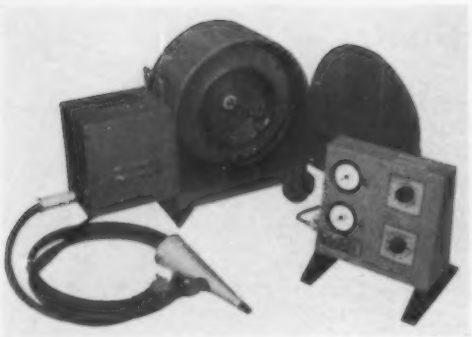
The use of standard automatic welding heads in this way shows another trend, evident in other directions and introduced by other companies, towards the development of versatile equipment that can be used for a variety of purposes. Thus, the Muramatic head can also be mounted on booms, mobile platforms and, according to the required conditions, can operate as a submerged-arc or an open-arc welder.

In a like way, the Lincoln twin-head tractor, which has been specially designed to speed fillet welding in shipyards, is interchangeable with other existing Lincolnweld units. This model too can operate as a submerged-arc or an open-arc unit.



Lincoln twin-head automatic submerged arc tractor unit

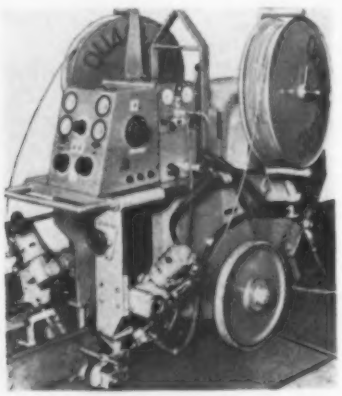
The Lincolnweld B.10 automatic submerged-arc head is designed rather differently. It is a stationary unit for mounting on a Lincoln retractable column and boom, and it is thus suitable for internal and external welding of vessels and pipes of all sizes. The wide



Manual semi-automatic submerged arc welding unit with remote control (Lincolnweld M.L.3)

allowances for movement of the head mean that fillets and laps can be made as easily as downhand welds. A similar head (B.11) can also be mounted on a self-propelled carriage travelling on a fixed beam.

A notable feature of Lincoln equipment is the care taken by the designers to cater for the minor but troublesome difficulties that arise from the use of automatic equipment. The B.10 has immediate contact starting by inching the electrode onto the work, so that the need for a wire-wool start is eliminated; the manual ML.3 submerged-arc unit has a remote control device so as to allow full control of the welding conditions in confined spaces remote from the power source.



Quasi-Arc self-propelled twin-fillet automatic welding machine

The Quasi-Arc twin-fillet welder has been successfully operating in British shipyards for some time. The machine exhibited was equipped for operation on the Fusarc/CO_2 process but it can also be adapted for submerged-arc welding. Of greater interest perhaps to the smaller fabricating shop was the Company's 'basic welding head', which enables a complete automatic welding unit to be built up from five basic assemblies. This provides a versatile unit at a considerably lower cost than a complete specialised machine. An example of a possible future development in this field is a Fusarc/CO_2 gun welder for semi-automatic manual welding.

Versatility was again shown in the Rockweld Autopak equipment, which can be used for fully automatic submerged-arc welding or for manual welding with normal covered electrodes. This unit has a very sensitive voltage control which ensures good penetration even with slight inaccuracies in fit-up, and an adaptation of the twin motor control unit provides the drive for the welding head carriage. By mounting the unit on a 20 ft boom the equipment can be used to make welds up to 17 ft 6 in. long at any height from the floor. The addition of further transformer units increases the capacity of the machine to 1200 amp.

Rockweld have overcome some of the inherent difficulties of the bare-wire CO_2 process by using in their Comet machine a special composite wire which includes ionizers and slag-forming elements. These

Equipment for the Rockweld Comet CO_2 process

provide stability to the arc and smooth contours with absence of spatter to the weld deposits; normal cylinder CO_2 provides the gas shield against atmospheric contamination. The Autopak welding head can be used with this system.

For most of the normal automatic equipment it is necessary that the joints should be reasonably straight or in smooth curves with only local small inaccuracies that can be accomodated by the automatic arc control provided. A useful contour-following device has been produced by Arc Manufacturing Co. Ltd., which will maintain a constant wire feed to produce the same weld profile regardless of the welding angles at which the work may be positioned. It will be interesting to see how this method is developed in other ways.

(To be continued)

Welding
RESEARCH

B.W.R.A. REPORT

Hot Cracking of Mild Steel Welds

FINAL REPORT ON HIGH-TEMPERATURE TENSILE TESTS

By P. W. Jones,
M.SC., A.I.M.

High-temperature tests on mild steel weld metals were carried out in vacuo *and in hydrogen and nitrogen atmospheres using a resistance-heated furnace. The results showed relatively low ductility in the range 950–1100°C., which was not appreciably affected by changes in the atmosphere. Similar results were obtained using rapid heating by high-frequency induction in an argon atmosphere. This minimum in ductility at about 1000°C. showed a very poor correlation with the susceptibility to hot cracking of the weld metals as assessed by Murex hot-cracking tests.*

Two wrought steels showed no minimum in high-temperature ductility corresponding to that of the weld metals, but a cast steel did show a minimum that was very similar. Hot rolling and swaging of weld metal did not eliminate the minimum but it was less pronounced after this treatment.

Dead load tests, carried out in an argon atmosphere at temperatures near the solidus, gave no correlation between temperature of rupture and the resistance to hot cracking of the weld metal.

KNOWLEDGE of the temperature at which hot cracking takes place might lead to a better understanding and to a mitigation of this defect. It might also enable a less arbitrary test of hot cracking susceptibility to be devised.

Ball and Winterton,[1] have been unable to draw conclusions about the temperature of hot cracking, or to show a good correlation between high-temperature ductility of weld metals and their susceptibility to hot cracking.

Their original work has been revised and extended, using improved apparatus; and, in addition to tests *in vacuo*, tensile tests were carried out at high temperatures in hydrogen and nitrogen atmospheres. Dead load tests were carried out in argon at temperatures around the solidus. Rapid heating by high-frequency induction was used in some of the work.

Some variations in welding procedure were made, but most of the tests were carried out on specimens of unrefined weld metal made with 4 s.w.g. electrodes.

Attention has thus been given to the mechanical properties of reheated weld metals at temperatures from 700°C. to the solidus, with appropriate comparisons with cast and wrought steels and with wrought weld metal.

Apparatus and Testing Procedure

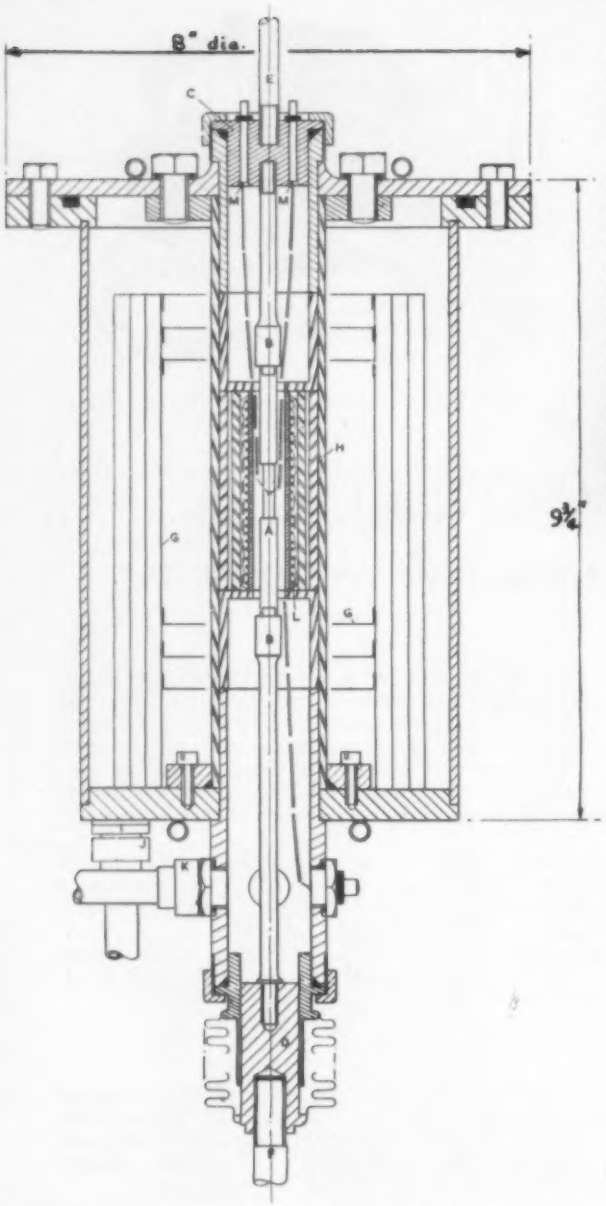
Resistance-heated furnace

The furnace shown in Fig. 1 was used for tests at high temperatures *in vacuo* or in gas atmospheres. It was based on that used by Ball and Winterton but was modified to achieve higher temperatures and lower pressures, and also to operate in various gases.

The specimen *A* was screwed into grips of Nimonic

Report FM.3/127/58 of the British Welding Research Association, issued to members in December 1958.

Mr. Jones, formerly a Senior Research Officer with the Association, is now with Marshall's Flying School Ltd., Cambridge.

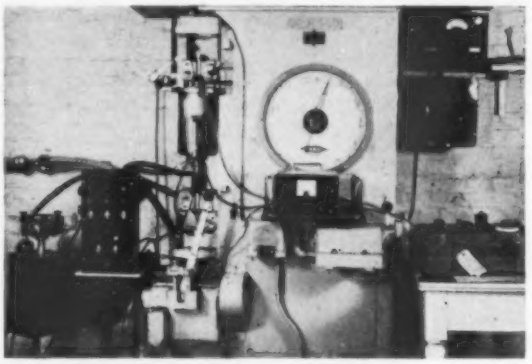


1—*Diagram of resistance heated furnace for high-temperature tensile tests*

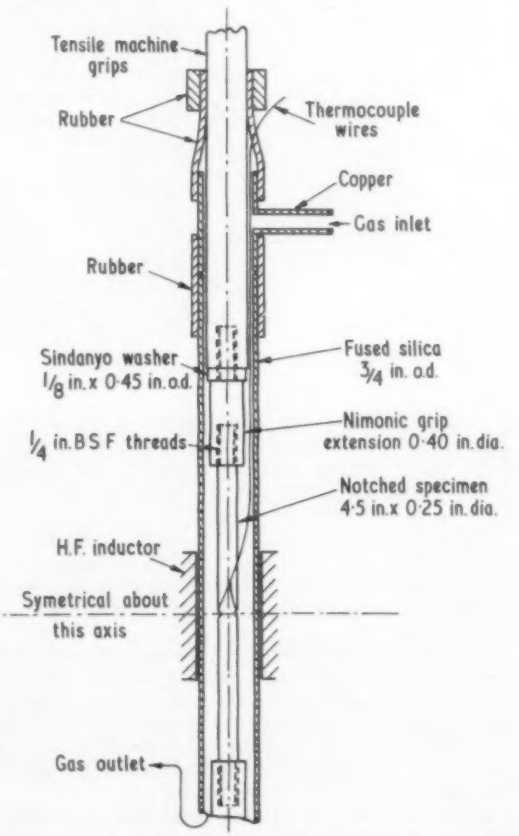
75 alloy *B*, which were screwed directly into the upper end *C* of the furnace and into the bellows *D* at the lower end. Two rods *E* and *F* carrying spherical seats (which transmitted the load applied by the tensile testing machine) were screwed externally into opposite ends of the furnace.

Thermal insulation was provided by copper radiation screens *G* in the space surrounding the main alumina tube *H*. This space was kept evacuated for the whole of the heating cycle, irrespective of the atmosphere used in the central specimen chamber.

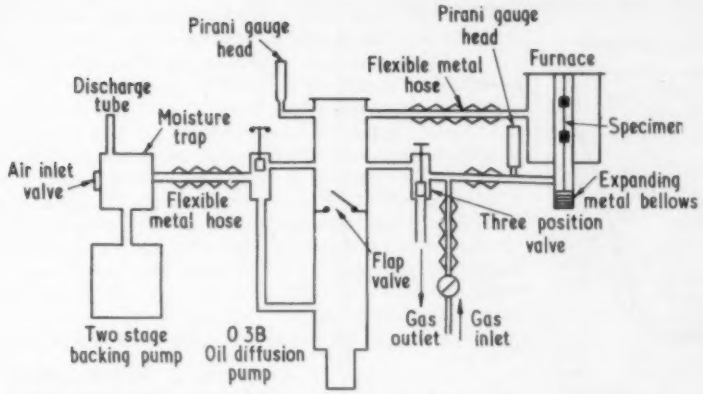
Evacuation took place through standard ⅛ in. vacuum unions *J* and *K* soldered to flexible metal hose. Gases, when required, were admitted to the previously evacuated space through the connection *K* at the lower end of the furnace.



2—*Apparatus for high-temperature tensile tests* in vacuo. *From left to right: Backing pump; control panel with diffusion pump behind; resistance heated furnace between specimen grips, with Pirani gauge head in front; load indicating dial, with Pirani gauge below; thermocouple potentiometer on table with electricity supply panel for furnace windings on wall above*



3—*Gas shroud for tensile testing in argon or other gas, using 6 kW h.f. heater*



4—Diagram of complete vacuum system

Because it was intended to carry out tests in hydrogen, all refractories were of impervious recrystallized alumina, and the Pt–10%Rh heating element *L* was set in silica-free alumina cement. The temperature could be maintained to within ±2°C. without difficulty by means of a manually-operated variable transformer.

Temperature was measured by a thermocouple tied to the centre of the specimen, and connected through vacuum seals *M* by compensating leads to a potentiometer. Generally, thermocouples of Pt–13%Rh/Pt alloy were employed. The 5%Rh–20%Rh combination was also used, but it did not appear to have any advantages for this work.

Pressure was measured by a small commercial Pirani gauge, with its head mounted as near to the furnace chamber as possible, although it was not possible to mount it on the furnace. Pressure readings obtained were generally 0·004 mm of mercury or lower, although higher readings were obtained during the heating period, mainly due to gassing of refractories. When comparing this pressure with those quoted by other workers it should be remembered that the Pirani gauge is sensitive to the presence of condensible vapours, and where these are not removed by cold trap, it gives a higher reading than an absolute gauge of the Macleod type.

The arrangement of valves for admitting gases to the evacuated space is shown in Fig. 4; but for testing *in vacuo* these valves were omitted.

In a typical test run, the furnace was assembled with the specimen in position and fitted between the grips of the tensile machine (see Fig. 2). Before evacuating the furnace, a small tensile load was applied, sufficient to counteract the air pressure on the bellows. Evacuation required about 15 min, then heating began and took about 30 min to reach the desired temperature, during which time the thermal expansion of the specimen and grips was taken up by continual adjustment of the extension applied by the testing machine so as to avoid buckling. The temperature was held steady for 5 min before breaking the specimen. Afterwards, the vacuum was maintained until the furnace had cooled to below 200°C.

High-frequency heating

This was used for tensile tests in argon. The apparatus consisted of a tube of silica or Pyrex glass, which surrounded the specimen, as shown in Fig. 3. Argon of 99·8% purity was passed through the tube at 15 cu.ft/hr. The heating was provided by a 6 kW induction heating unit. The use of a specially designed single-turn output transformer or 'concentrator' enabled a specimen to be heated to 1000°C. in about 10 sec; but to give a steady temperature, heating cycles were adopted which enabled the specimen to be broken after about ¾ min.

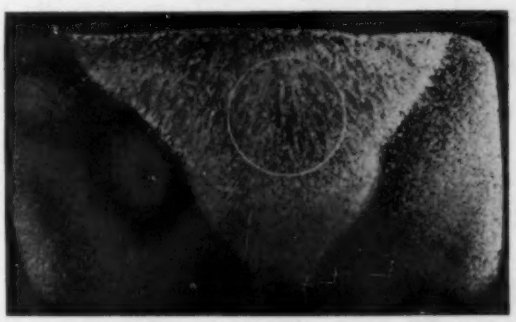
Temperatures were measured by thermocouples flash-welded to the specimen and connected to a high-speed potentiometric recorder. Temperature distribution was checked over a 0·73 in. gauge length by three independent thermocouples. Gradients of a serious nature were found which were never entirely overcome, so that notched specimens for which the temperature distribution was less important were used with this apparatus.

Welding procedures

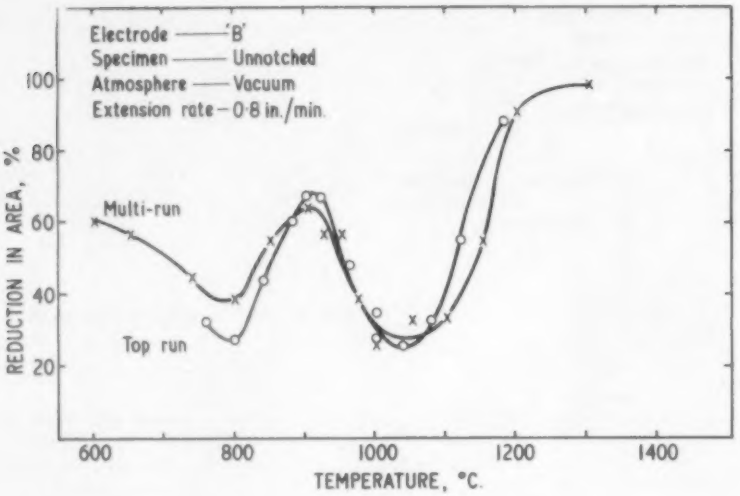
Multi-run specimens—Butt welds were made between ½ in. mild steel plates of similar composition, and falling within the range:

C	0·19 –0·22%
Mn	0·57 –0·65%
Si	0·13 –0·17%
S	0·054–0·061%
P	0·018–0·035%

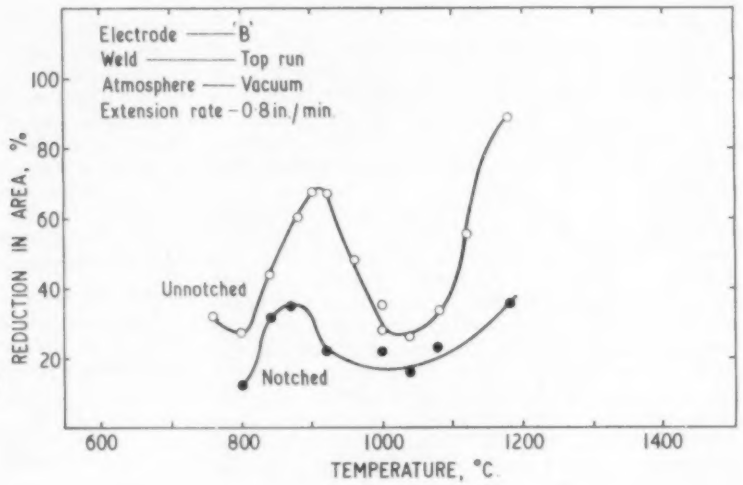
Four runs were deposited from 8 s.w.g. electrodes in a 60° single-**V** preparation with a root face of $\frac{1}{16}$ in. and a root gap of $\frac{1}{8}$ in. An alternating current of 170 amp was used throughout. Before the first run the plate was preheated to 120°C. Each weld was 6 in.



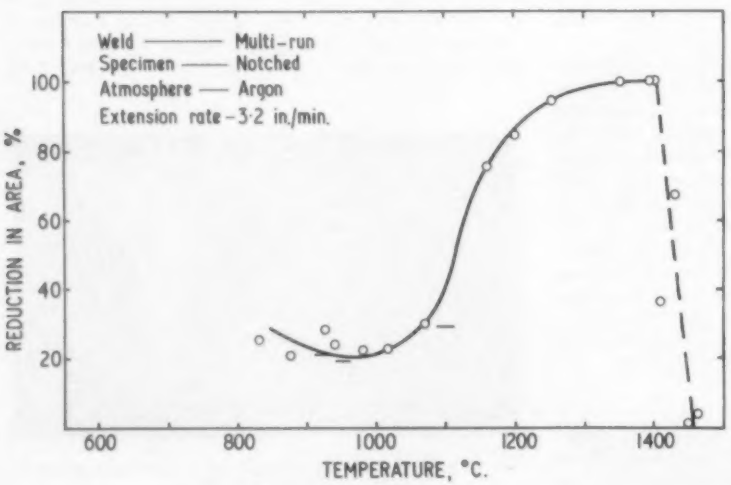
5—Typical macrostructure of weld made by revised procedure. Circle represents test bar dia. of 0·206 in.



6—*Comparison of ductilities of weld metals made with different welding procedures*



7—*Comparison of ductilities of notched and un-notched specimens*



8—*Ductility of notched specimens of weld metal from electrode B in argon atmosphere, using h.f. heating. (Short horizontal lines indicate tests for which an accurate temperature reading could not be obtained.)*

long and one specimen ($4\frac{1}{2} \times \frac{1}{4}$ in. dia.) which contained portions of the second, third, and fourth runs, was machined lengthwise from the weld metal.

Top-run specimens—To obtain specimens from the unrefined top run of weld metal the plate was preheated to 150°C., and one run of 8 s.w.g. electrode was deposited, using the same plate preparation as before, but reducing the root gap to $\frac{3}{32}$ in. and the current to 162 amp. The second run was then made using a 4 s.w.g. electrode. Low-hydrogen electrodes were used with a current of 285 amp, and to obtain a sufficiently heavy deposit the plate was sloped at 15°. For other electrodes the current was 290 amp and the plate inclination 30°. It was possible to machine a tensile specimen entirely from the unrefined top run (Fig. 5).

Specimen shapes

Parallel or unnotched type—This was of conventional pattern, having a reduced parallel portion of 0·206 in. dia., equivalent to a cross-sectional area of $\frac{1}{30}$ sq.in.

Notched type—The notch had an included angle of 45° and a root radius of 0·005 in. The area remaining at the root of the notch was the same as on the unnotched specimens.

Results and Discussion

Effect of welding procedure and specimen type

Specimens of both top run and multi-run types tested under identical conditions gave similar temperature/ductility curves (Fig. 6).

With induction heating, notched specimens were used because it was difficult to measure the temperature of fracture of unnotched specimens owing to non-uniform heating. It was also hoped that notching might reveal brittleness at certain temperatures. The effect of notching, shown by some tests carried out in the resistance-heated furnace (Fig. 7), was to decrease the reduction in area at all temperatures, although not uniformly so. As changes in ductility with change of temperature were more readily shown by using specimens with parallel gauge lengths, subsequent tests were carried out with such specimens in the resistance-heated furnace.

Tests in argon using high-frequency heating

Tensile tests—High-frequency heating was quite satisfactory for notched specimens. Since these tests were made on reheated weld metal, the rapid heating, which permitted specimens to be broken in under one minute, was a great advantage over resistance heating, minimizing changes due to diffusion which would tend to promote homogenization.

Results for multi-run welds are shown in Fig. 8, which indicates an apparent scatter at the lower-temperature end of the curve. The possibility that this might be due to the heterogeneous nature of the specimens, which contained both refined regions and also coarse columnar crystals, subsequently led to the choice of specimens machined entirely out of one large run of weld metal.

The relatively poor ductility in the region of 950°C. agrees with the earlier work of Ball and Winterton. Higher temperatures have now been achieved, revealing a sudden drop in ductility at about 1400°C. This drop is probably due to incipient fusion, and its temperature might be expected to be influenced by the presence of low melting point impurities and possibly to bear some relation to susceptibility to hot cracking. Two series of dead load tests were carried out to investigate this.

Table I

Dead load tests compared with crack length (1st Group)

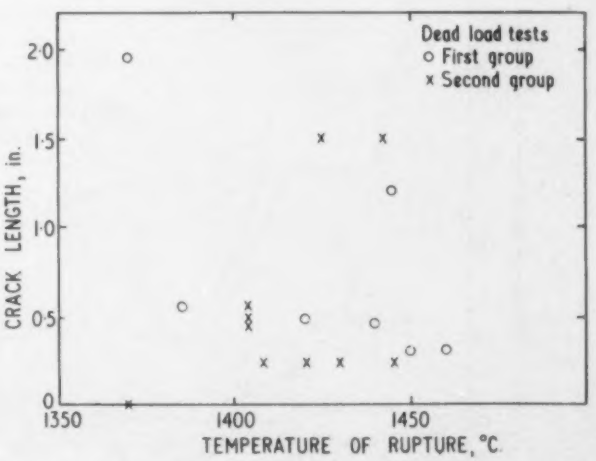
Electrode BS.1719 class	*Code*	*Red. in Area, %*	*Temp. of rupture, °C.*	*Crack length (Murex test), in.*
E219	B	1·1	1450	0·3
E219	B	3·7	1460	0·3
E319	E	0·5	1385	0·56
E537	J	—	1445	1·2
E614	N	nil	1440	0·43
E646	AP	3·4	1420	0·49
High Sulphur	V	0·5	1370	1·95

Table II

Dead load tests compared with crack length (2nd group)

Electrode BS.1719 class	*Code*	*Weld Metal Type*	*Time to Failure, sec*	*Temp. of Failure, °C.*	*Crack length (Murex test), in.*
E319	E	Top run	50	1425	1·5
E319	E	Top run	53	1443	1·5
E319	E	Multi-run	51	1404	0·56
E614	N	Multi-run	48	1467	0·43
E614	N	Multi-run	54	1404*	0·43
E616	AO	Top run	48	1420*	0·23
E616	AO	Top run	51	1446	0·23
E616	AO	Top run	54	1408	0·23
E616	AO	Top run	54	1430†	0·23
E616	AQ	Multi-run	54	1370	nil
E616	AQ	Top run	53	—**	nil
E646	AP	Multi-run	53	1404	0·49
S-impreg.	E	Top run	52	—**	—

* Different heating rate † Previously heated
** Broken thermocouple



9—Dead load tests plotted against results of hot cracking tests

Table III

Composition and other data relating to weld metal specimens

Electrode		*Weld metal composition, %*				*Mn/S*	*Approx equiv. crack*	*Min. Red. in Area*
BS.1719 class	*Code*	C	Mn	Si	S	*ratio*	*length in Murex test, in.*	*at about 1000°C., %*
E219	B	0·064	0·60	0·12	0·045	13·3	0·75	27
E319	E	0·044	$0·42_2$	0·13	$0·037_8$	11·1	1·3	27
—	E (S-impreg.)	0·081	$0·41_8$	—	$0·054_7$	7·7	2·05	24
E646	AP	0·128	$0·45_4$	—	$0·032_6$	13·8	0·65	52
E614	N	0·092	$0·74_2$	—	$0·029_3$	25·4	0·2	49
E616	AQ	0·085	1·00	—	0·028	35·6	nil	37·5
E616	AO	0·052	$0·81_8$	—	$0·027_2$	30·1	0·1	43
E616	AO*	0·18–0·27	$0·85_6$	—	$0·025_6$	33·4	—	37
E319	E (wrought)	0·02	0·42	—	0·032	13·1	0·8	64

* Carburized plate

Dead load tests—The tests were made in the simple apparatus shown in Fig. 3, to see if any correlation could be obtained between the hot cracking tendency of the electrode and the temperature of complete rupture of a notched specimen of the weld metal under a small tensile load. This was done because of the slowness of the method of rupturing specimens at various steady temperatures used to plot a ductility/temperature curve.

The first series of tests was made with the weight of the lower wedge grips, 1·46 kg, hanging on the specimen, and the second in a separate loading jig with a total hanging load of 3·46 kg. In both tests the temperature was increased steadily until failure occurred. In the first series the heating rate was such that failure occurred in about 1–2 min, whilst in the second, more rapid heating in the early stages produced failure in about 50 sec.

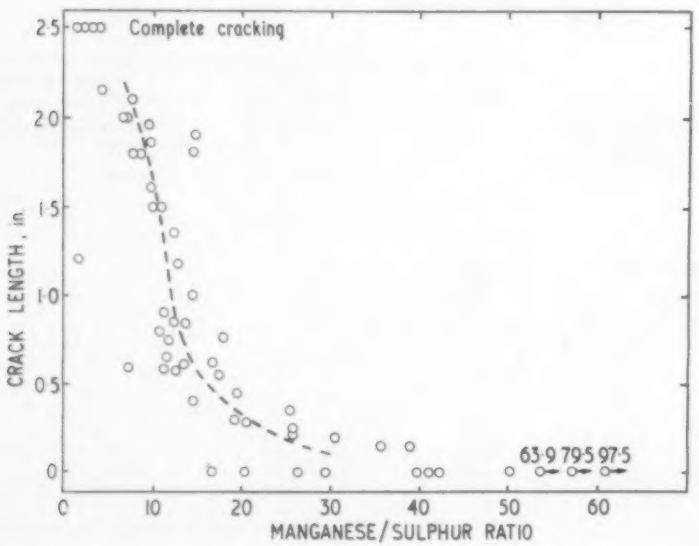
The results of the tests are given in Tables I and II and in Fig. 9. All fractures were brittle and no appreciable reduction in area occurred in any test. The broken specimens were not analysed, so that it was not possible to take into account the differences in composition between the specimens and corresponding Murex test welds made with the same batches of electrodes.

There is no correlation between the temperature of rupture and the hot-cracking tendency as shown by the Murex test. This temperature of rupture should be related to the solidus temperature. Despite probable differences in composition, the results of dead load tests suggest that hot cracking does not occur in mild steel at solidus temperatures.

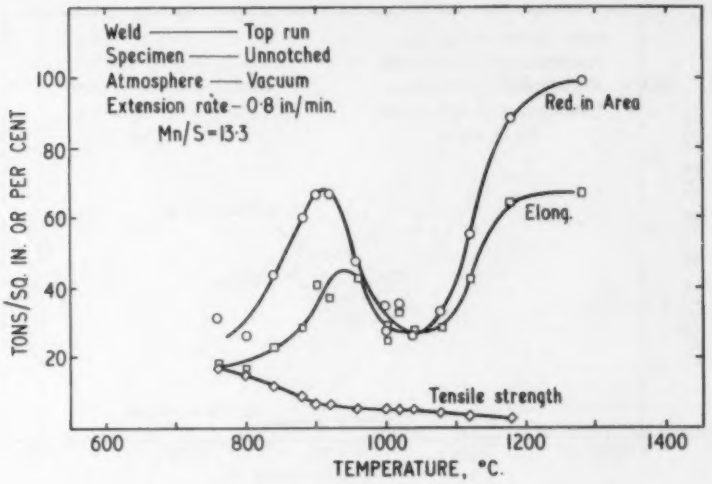
Comparative tests on various weld metals

Direct and accurate comparison between the high-temperature ductility of a weld metal and its hot-cracking properties was not possible, because the Murex hot cracking test required a different gauge of electrode from that used for the all-weld tensile specimen. Moreover, the welds had different dilutions and therefore different final compositions.

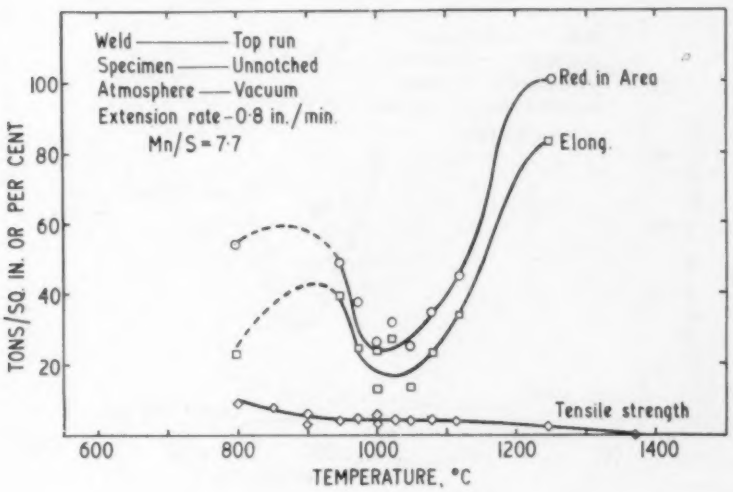
The susceptibility to hot cracking of a number of weld metals made with various commercial electrodes has already been evaluated with the Murex hot cracking test.[2] Chemical analysis of a large number of test welds has revealed the relationship between Mn/S ratio and crack length, as shown in Fig. 10. This



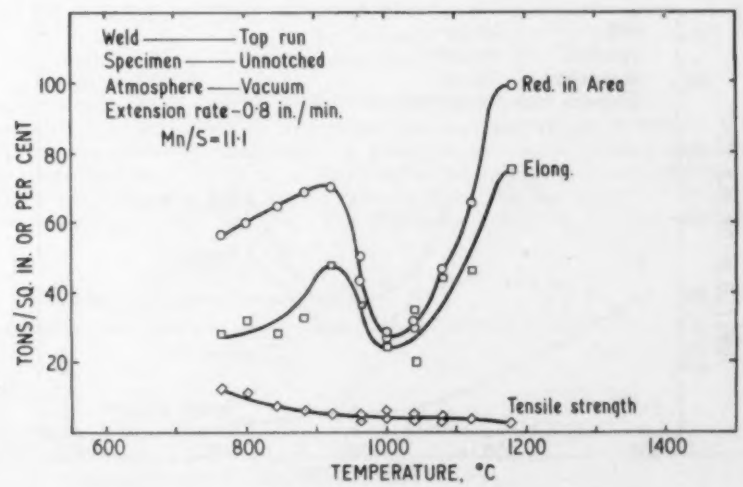
10—*Manganese/sulphur ratio of weld metals plotted against crack length in Murex test*



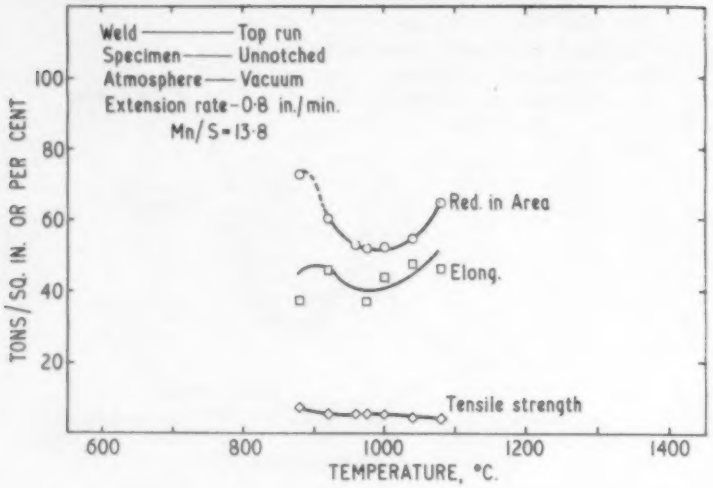
11—*High-temperature tensile properties of weld metal from electrode B*



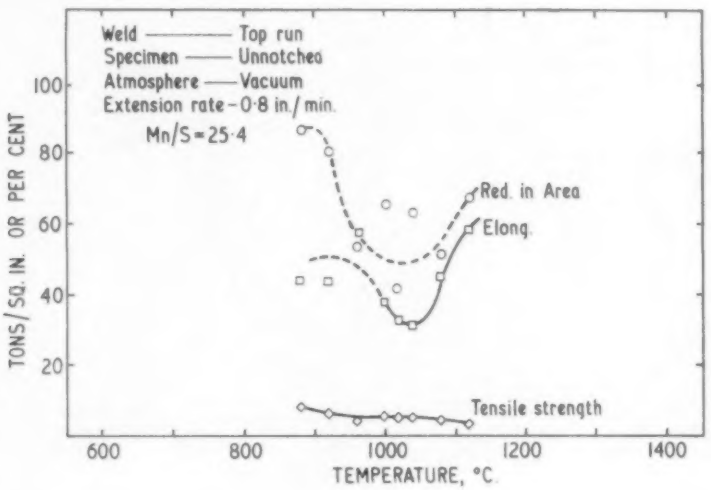
12—*High-temperature tensile properties of weld metal from sulphur-impregnated electrodes* E



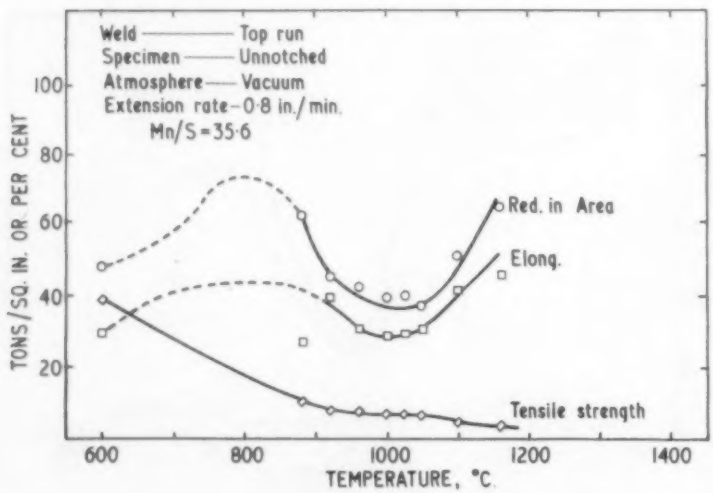
13—*High-temperature tensile properties of weld metal from electrodes* E



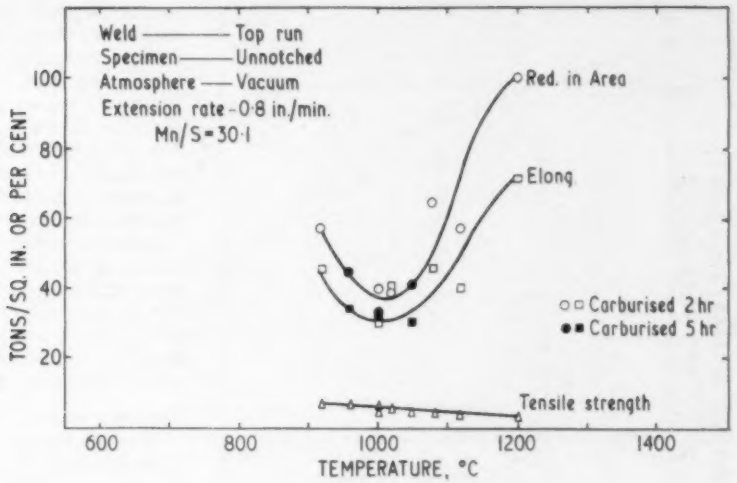
14—*High-temperature tensile properties of weld metal from electrodes* AP



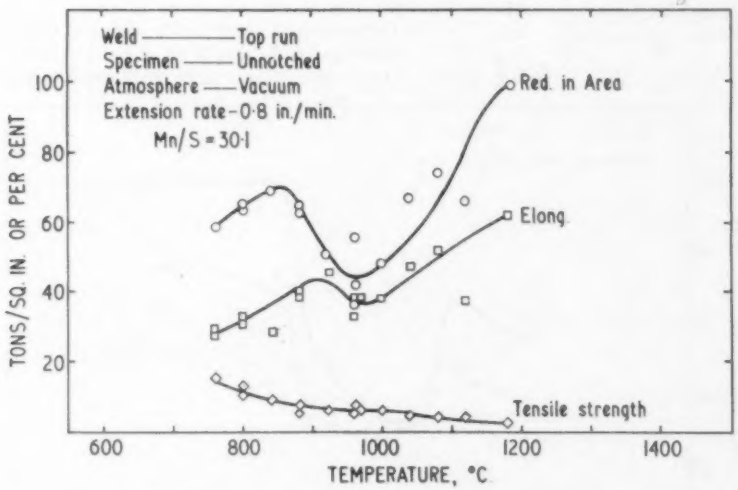
15—*High-temperature tensile properties of weld metal from electrodes* N



16—*High-temperature tensile properties of weld metal from electrodes* AQ



17—*High-temperature tensile properties of weld metal from electrodes* AO *using carburized plate*



18—*High-temperature tensile properties of weld metal from electrodes* AO

relationship was used to derive a measure of the hot cracking propensities of the all-weld tensile specimens from their manganese and sulphur contents.

High-temperature tensile tests were carried out on specimens welded with a range of electrodes chosen to give as wide a range of Mn/S ratios as possible. To obtain a particularly low ratio, electrodes of artificially increased sulphur content were used. The various results and compositions are given in Table III and in Figs. 11–16 and Fig. 18. Figure 19 shows that there is no satisfactory correlation between ductility and composition although there is a sharp rise in ductility at a Mn/S ratio of 14, which is in fair agreement with the sharp drop in hot cracking susceptibility which occurs at about the same Mn/S ratio.

Effect of sulphur impregnation

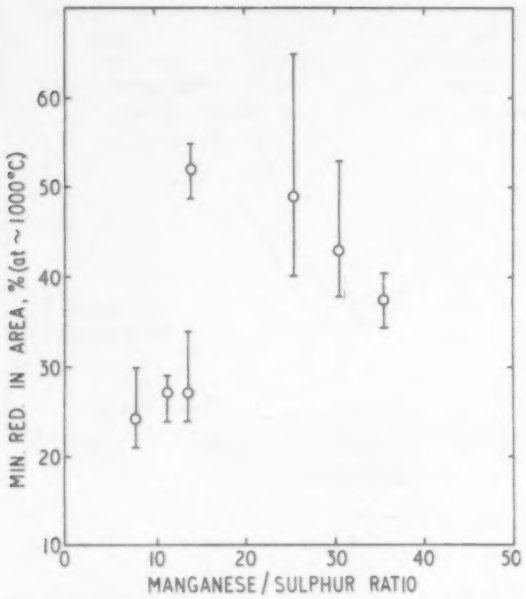
Impregnation was carried out by immersing the electrodes for 2 min in carbon disulphide containing 31 g/l of dissolved sulphur. This treatment increased the sulphur content of the weld metal from 0·038% to 0·055%. The minimum reduction in area at high

Table IV

Analyses of cast and wrought steels

Steel	*Composition, %*									*Resid. Hydrogen,*
	C	Si	Mn	S	P	Ni	Cr	Mo	V	ml/100 g
Cast steel*	0·19		0·48	0·024						
En 9 plate	0·52	0·23	0·69	0·05	0·031	0·19	0·09			0·05
En 28 plate	0·30	0·23	0·59	0·013	0·014	3·38	0·75	0·62	0·08	

* Believed to be low-carbon Bessemer



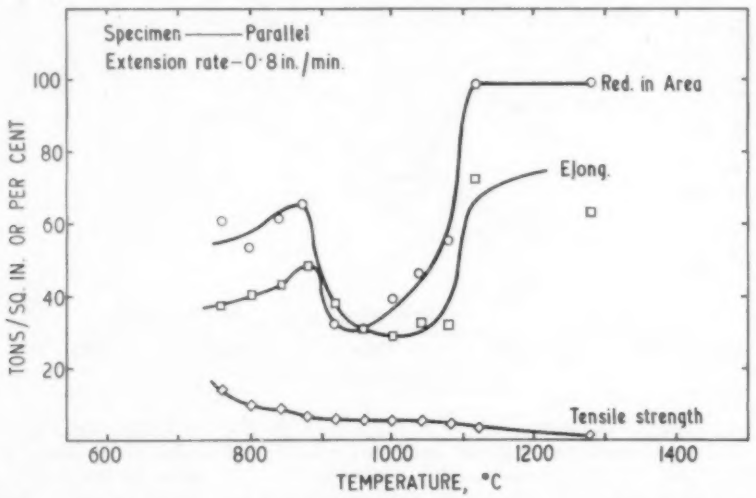
19—*Poor correlation between ductility and Mn/S ratio (Vertical lines show probable error at each point)*

ing the prepared plates before welding. The plates were carburized in two batches, for 5 hr (early tests) and for 2 hr. These treatments gave carbon contents in the tensile specimens of 0·27% and 0·18% respectively. Figure 17 shows that there is little difference in the ductility of the two batches, but comparing it with Fig. 18 it is evident that carburizing has produced a significant diminution of the minimum ductility, although the ductility at 1200°C. has not been affected appreciably.

Added sulphur and added carbon have had similar effects on the high-temperature ductility, both having reduced it by a small amount (Figs. 12 and 13, 17 and 18). In view of the known markedly detrimental effect of carbon on hot cracking[3] a much larger effect on the ductility minimum would be expected if the two phenomena were related.

Cast and wrought steels

The mechanical properties of one cast and two wrought steels (Table IV) were determined over a wide temperature range *in vacuo*, using the resistance-heated furnace. The results are given in Figs. 20, 21 and 22. The two wrought steels have high ductilities from 800° to 1400°C., and there is no reduction in the 900–1100°C. region as in the case of weld metals. The



20—*Tensile properties of cast steel* in vacuo *at various temperatures*

temperature was reduced from 27% to 24% by this increase in sulphur. The reduction, although quite small, is significant (Figs. 12 and 13). The sulphur impregnation did not produce any brittleness at 1200°C. at which temperature the reduction in area exceed 99%.

This comparatively mild impregnation with sulphur produced considerable porosity in the weld metal, and many test results were discarded because the specimens were unsound.

The increase in sulphur due to this treatment was sufficient to cause severe hot cracking in the Murex test, and the small effect on ductility at high temperatures is surprising.

Effect of increased carbon

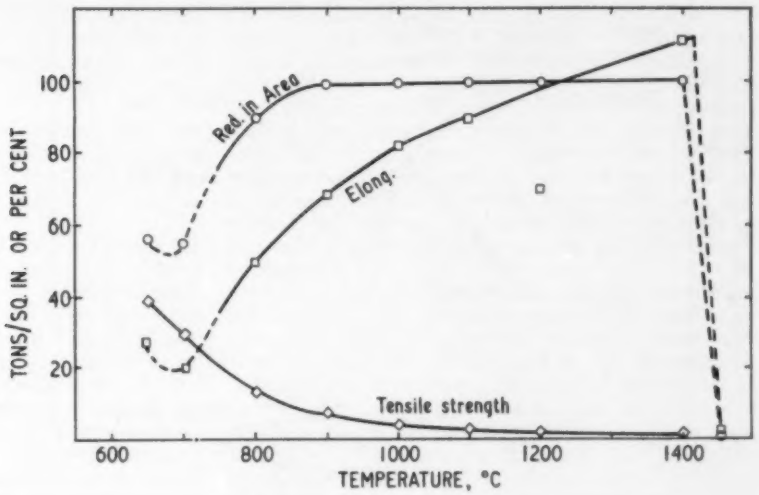
The carbon content of the weld metal was increased without affecting other elements by pack-carburiz-

cast steel, however, shows a very considerable drop in ductility (Fig. 20) and its reduction-in-area curve is very similar to that for the weld metals. These results are in agreement with those of Ball and Winterton[1] and confirm that, with respect to high-temperature tensile properties, mild steel weld metal resembles cast, and not wrought steel.

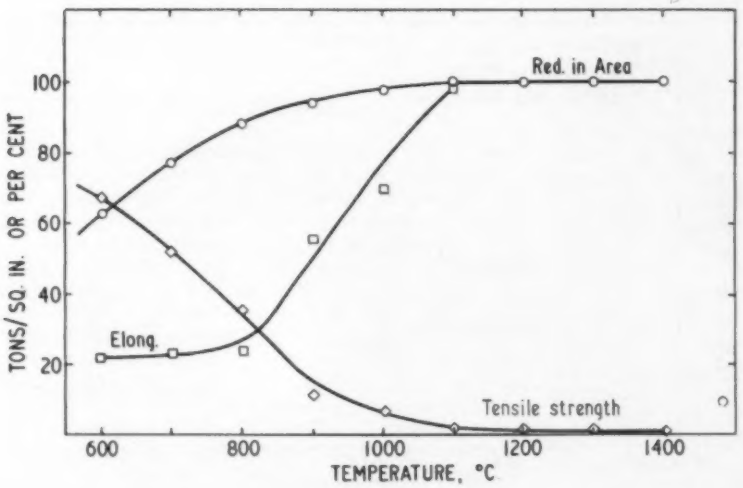
Effect of mechanical working

The foregoing results show that the effect of mechanical working on cast steel is to remove completely the minimum in high-temperature ductility. It was considered valuable to find out if the minimum for weld metal was similarly affected by hot working.

An exceptionally large multi-run weld was made using 4 s.w.g. electrodes. From this, a $\frac{7}{8}$ in. dia. rod of weld metal was machined. This was rolled to $\frac{3}{8}$ in. dia. from 1100°C. using several reheats. After shot blasting



21—*Tensile properties of En.9 steel* in vacuo *at various temperatures*



22—*Tensile properties of En.28 steel* in vacuo *at various temperatures*

it was then swaged cold to 0·325 in., normalized, and finally swaged cold to 0·245 in. dia.* Parallel-type tensile specimens were then machined from the rod and tested in the resistance-heated furnace. The chemical analysis is given in Table III.

A considerable minimum in ductility at about 1000°C., still remains after this treatment (*cf.* Figs. 13, 23). This minimum has not been observed in wrought steels, but the amount of hot work they had received was probably greater than had been applied to the weld metal. Despite the difference in amounts of hot work, the results suggest that the ductility minimum in weld metal may be a different phenomenon from the minimum shown by cast steel.

At 1200°C., the hot-worked weld metal shows a lower ductility than either the 'cast' weld metal or the wrought steels which have been examined.

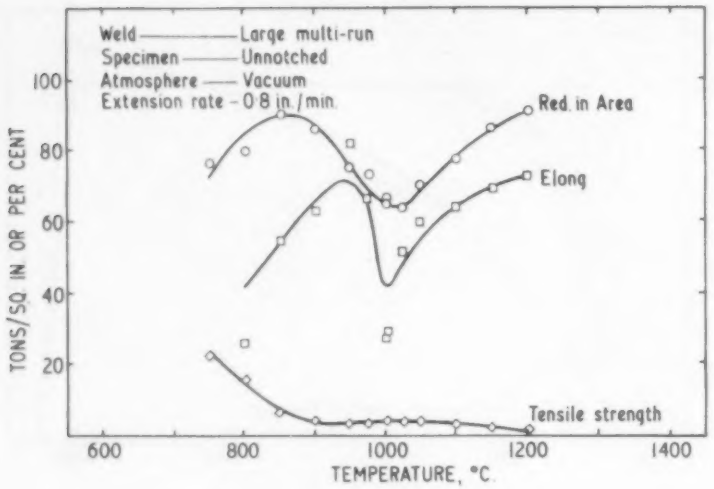
Tests in hydrogen and nitrogen atmospheres

For test in gas atmospheres, the gas was admitted to the evacuated furnace and the pressure was raised to atmospheric before commencing to heat. Heating rates were somewhat slower owing to loss of heat by convection. Otherwise, the tests were identical to those carried out *in vacuo*.

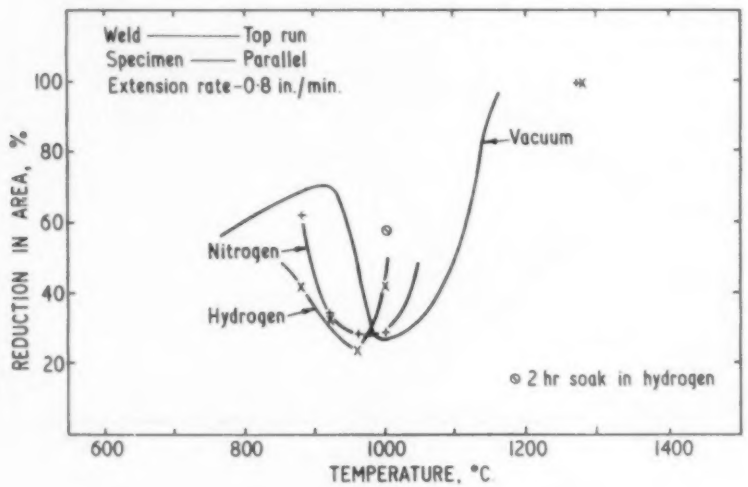
Specimens of two weld metals, one relatively susceptible (electrode *E*) and one relatively insusceptible (electrode *AO*) to hot cracking in the Murex test, were tested in each of the two gases at temperatures of 900–1000°C., and also at 1280°C. The results are given in Figs. 24 and 25. At 1280°C. very high ductilities were obtained in both gases, and there seemed to be no detrimental effects. In the 900–100°C. region, slight differences were seen.

One specimen was held in hydrogen for 2 hr at 1000°C. before extension was applied. This gave a reduction in area of 58% (Fig. 24) compared with 42% for the corresponding specimen broken in hydrogen after the standard 5 min soaking time. Ball and Winterton[1] found that holding at elevated temperature *in*

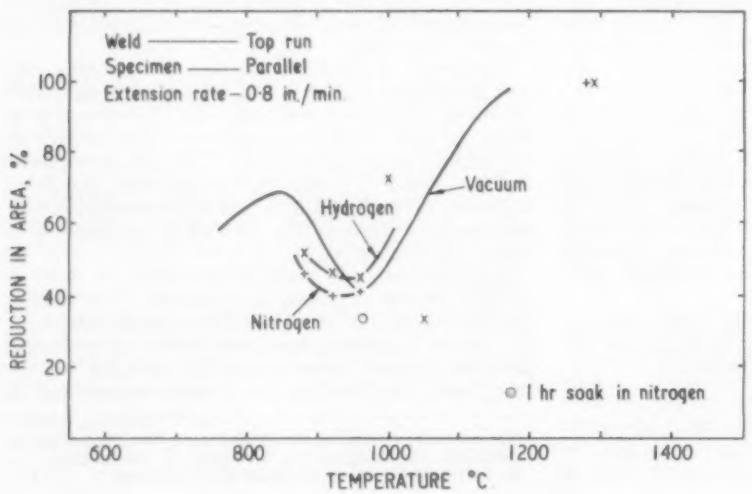
* The mechanical working was carried out in the Department of Industrial Metallurgy at the University of Birmingham, for which thanks are due to Professor E. C. Rollason.



23—*High-temperature tensile properties of weld metal from electrode E after hot rolling and swaging*



24—*Comparison of ductilities of weld metals from electrode E tested in different atmospheres*



25—*Comparison of ductilities of weld metals from electrodes* AO *tested in different atmospheres*

vacuo caused an increase in ductility, so that the present increase was not necessarily due to hydrogen. Ductility was very sensitive to small temperature changes in this region, so that the experimental error may have been considerable.

A specimen of weld metal from electrode *AO* was soaked in nitrogen for 1 hr at 960°C. This decreased the reduction in area from 41·8% (for a 5 min soak) to 33·8% (Fig. 25). It is difficult to establish whether this is significant or not.

Within the limits of experimental error, the two gas atmospheres, hydrogen and nitrogen, appear to have had no effect on the magnitude of the ductility minima. The positions of these minima appear to have been moved to slightly lower temperatures. This may have been caused by the lower heating rate, or by some alteration in the temperature distribution in the furnace, brought about by convection currents. As the gases used were molecular, and the amount which dissolved in the specimens is not known, this experiment does not prove that hydrogen and nitrogen are not responsible for hot cracking, but none of the results gives grounds for suspecting that either of these gases plays any part in the phenomenon.

General Discussion

Some explanation should be sought for the low ductility that occurs in mild steel weld metal and in cast steel at temperatures of about 1000°C. If the phase change from ferrite to austenite during reheating were responsible, wrought steels would also be expected to show a similar range of low ductility. For a more likely explanation, reference may be made to the iron-sulphur binary phase diagram.[4] In alloys containing between 0·01% and 0·18% of sulphur, the completely solid alloy can deposit liquid iron sulphide within the region 1365–988°C. For example, a 0·02% sulphur alloy will produce a small quantity of liquid phase as the temperature falls below 1100°C. The presence of liquid phase along grain boundaries will undoubtedly cause hot shortness. The weld metals investigated contain considerable quantities of manganese, which, owing to its affinity for sulphur will tend to reduce the formation of liquid iron sulphide. Weld metal freezes rapidly, so that conditions are further from equilibrium than for steel castings. This may explain why such a large amount of manganese is required to prevent hot cracking—more than is needed to prevent hot shortness in steel ingots. The improvement in ductility produced by holding at temperature is probably due to reactions involving a nearer approach to equilibrium, such as the replacement of iron by manganese in the inclusions, as shown by Whiteley[5] for steel ingots.

In view of these considerations, a likely explanation for the low ductility of weld metals in the 1000–1100°C. region is the formation of small quantities of liquid sulphide in the grain boundaries. A surprising result is the slight effect of the microstructure of weld metal on the temperature/ductility curves, given in Fig. 6. One might have expected the coarser structure to have shown inferior ductility. The less pronounced minimum in wrought weld metal is not inconsistent with this explanation, since, owing to the much smaller degree of working for this material, compared with the wrought steels, it can be postulated that the sulphide inclusions have suffered a much smaller degree of break-up and alteration of constitution. This effect could be checked by high-temperature tensile tests on specimens from steel which had undergone a small reduction similar to the wrought weld metal. However, a more powerful method of investigating the hypothesis that the low ductility is due to sulphur-rich inclusions would be to make and test sulphur-free steel and weld metal. These would not be expected to show any minimum in ductility at high temperature.

In the present investigation the attempts to correlate hot cracking with the temperature of the solidus or with a temperature region of low ductility have both been unsuccessful. Although Fig. 19 shows little correlation between hot cracking and low ductility at about 1000°C., certain trends can be discerned which suggest a relation between these two factors. This would tend to support though not prove the hypothesis that hot cracking occurs around 1000°C.

The essential weakness of the tests reported is that they have all been performed on reheated weld metal. No evidence has been produced relating the tests to the mechanical properties of weld metal on first solidification and cooling. One major consequence of reheating would be to promote homogenization. The effect of this on the test results is not known. It appears likely that direct methods of measuring cracking temperature, such as that used by Antonioli,[6] might offer more promise, despite basically difficult experimental techniques.

Conclusions

1. There is little correlation between the susceptibility of weld metals to hot cracking and the value of the minimum reduction in area obtained in high-temperature tensile tests at about 1000°C.
2. There is no correlation between the susceptibility of weld metals to hot cracking and their temperature of rupture under a small dead load.
3. Neither the minimum ductility of weld metals in the temperature range 900–1100°C. nor the ductility at 1280°C. is appreciably influenced by atmospheres of hydrogen or nitrogen.
4. The ductility of weld metal in the temperature range 750–1200°C. is not sensitive to the changes in microstructure between an unrefined top run and normal weld metal produced by a multi-run technique.
5. Weld metal, after limited hot work, still shows a minimum in ductility at about 1000°C., but much reduced in its severity.

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B.W.R.A. REPORT

An Investigation of Hot Cracking in Low-Alloy Steel Welds

By P. W. Jones, M.SC., A.I.M.

This is the first part of a paper on the weld metal cracking of low-alloy steels. It describes an investigation of the hot cracking of weld metal deposited on various steels of this type. The effects are shown of some alloying elements (carbon, nickel, copper, chromium, and aluminium) which might be derived either from the electrode or from the alloy steel plate. The effects of preheating and weld size are also considered.

Within the normal limits, the effects of both factors are negligible. It is concluded that, to ensure freedom from hot cracking, composition limits for the weld metal should be specified, and suggested limits are given.

IN THE history of welding low-alloy high-strength structural steels, cracking in the heat-affected zone has been an obvious problem, and considerable effort has been devoted to its study.* In addition to this form of cracking, welds in such steels might be liable to cracking in the weld metal itself. Since any form of cracking might endanger the safety of the welded structure, a study of weld metal cracking has been undertaken and this paper describes the part of the work devoted to hot cracking. A parallel investigation of cold cracking (fissuring) is to be reported by T. E. M. Jones.[1] From a practical viewpoint it was desired to show whether weld metal cracking could still occur under conditions that were safe from heat-affected zone cracking. It was also intended to provide information that would lead to the specification of a test or the precautions needed to avoid weld metal cracking.

Present State of Knowledge

Hot cracks are those which form during solidification or cooling of a weld. For aluminium alloys,[2, 3] it has been established that cracking generally occurs at temperatures above the solidus, and is substantially the same phenomenon as the hot tearing of castings. For steel, there is still doubt whether the cracks occur at temperatures above or below the solidus, but it is generally accepted that they occur at very high temperatures, certainly above 1000°C. Other types of crack may occur at lower temperatures.

A hot crack in a metal-arc weld in steel is normally longitudinal through the throat of the weld. It can usually be seen as soon as the slag is removed, although occasionally it may be so narrow as to be invisible to the naked eye. The surfaces of the cracks exhibit a characteristic blue colour, and under the microscope the intercrystalline nature of the fracture is readily apparent. In contrast, fissures which are formed at or near room temperature are generally transcrystalline. It is often thought that hot cracking of welds is the same phenomenon as hot tearing of castings; for steel, as in aluminium alloys mentioned above, the two defects have many similarities.[4, 5] According to Apold,[6] the stresses causing hot cracking are raised by increased rigidity of the element, or by concavity of the bead surface; convexity reduces the stresses.

Notable reviews of the literature have been published by Williams, Rieppel, and Voldrich,[7] and by Spraragen and Claussen.[8] It is clear[5, 7] that sulphur is primarily responsible for hot cracking, and that manganese is beneficial in counteracting the effect of sulphur.[7] Carbon has been shown to be detrimental to hot cracking,[5, 9, 10] although it has been suggested[6] that the cracks associated with high carbon content are different in form and appearance from those due to sulphur. The effect of 0·5% nickel has been found[11] to be detrimental, while molybdenum is reported[6] to be beneficial. Boron is stated[6] to promote red shortness in steel and to give a pronounced hot-cracking tendency.

The mechanism of hot cracking has genera'ly been supposed to be a weakening of the cooling weld caused by the presence of a liquid film rich in impurities and of low melting point. This theory appears to explain the two best known facts about hot cracking. The deterimental effect of sulphur is explained by its tendency to form sulphides of low melting point. The

* See for example "Arc welding low alloy steels" British Welding Research Association, 1956.

Part 1 of Report FM.3/128/58 of the British Welding Research Association, issued to members in December 1958.

Mr. Jones, formerly a Senior Research Officer with the Association, is now with Marshall's Flying School Ltd., Cambridge.

beneficial effect of manganese, which is known to have an affinity for sulphur, would result from the relatively high melting point of manganese sulphide.

Testing Methods

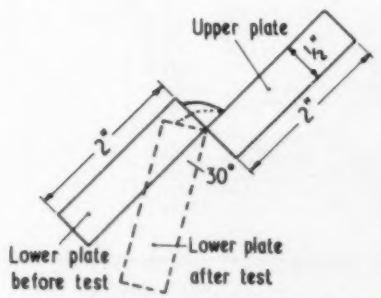
Five types of test were first tried to find a suitable method for assessing hot-cracking susceptibility. The tests were:

(i) A fillet weld laid over a controlled slit, machined parallel or transverse to the direction of welding
(ii) A weld laid from the edge to the centre of a square plate, using various forms of double-V or double-U preparation or alternatively a slot in the plate. Various plate thicknesses were used
(iii) A 'fishbone' test [12] consisting of a rectangular mild steel plate $4\frac{1}{2} \times 2\frac{3}{4} \times \frac{1}{4}$ in. thick containing a series of slots of graduated depth
(iv) A square test piece of 1 in. plate in which a circular groove was machined. (A weld made with a highly crack-susceptible electrode showed no visible cracking).
(v) The Murex hot-cracking test, in which a controlled relative motion is maintained between two test plates during the deposition of a fillet weld under standard conditions.

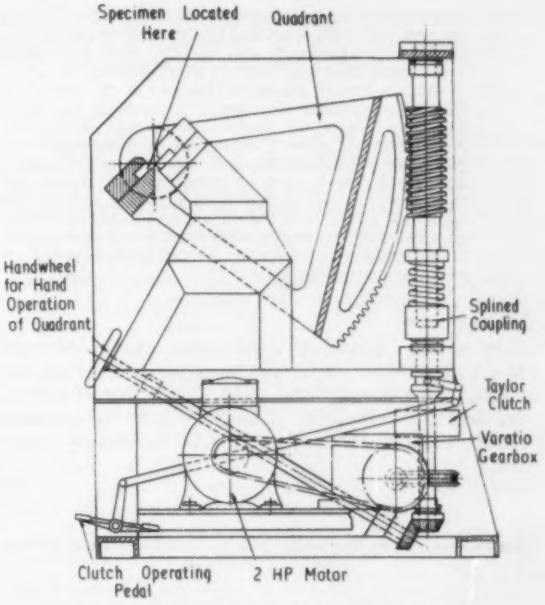
Consistent results were obtained only with the Murex test, and consequently this was adopted throughout the remaining investigation. Although it is possible that the other tests could have been developed to give consistent results, there was a good background of experience with the Murex machine,[13] and no development work was necessary.

Murex Hot-Cracking Test

The principle of the test is that a fillet weld is laid between two small plates $3 \times 2 \times \frac{1}{2}$ in. held in rigid clamps as indicated in Fig. 1. Five seconds after striking the arc, the rotation of one of the plates about the root of the weld is started so as to open out the weld. This rotation continues at constant speed until the moving plate has been turned through 30°. Various rotational speeds, numbered 1 to 9, can be used to suit the gauge of electrode and the severity of test required. The electric motor which applies the rotation is of sufficient power for the speed to be unaffected by the resistance to deformation of the weld metal. The machine is shown diagrammatically in Fig. 2. A detailed description has been given by Rollason.[14]



1—*Murex hot-crack test specimen, showing positions at start and end of test*



2—*Section through Murex hot-crack machine*

Any crack obtained usually runs longitudinally through the weld, and, since the rate of strain and the total strain applied to the fillet both diminish during welding, it is logical to assess the severity of cracking by measuring the length from the start of the weld to the end of the crack. Cracking in the weld crater is normally ignored, and complete cracking is reported as 2·5 in. allowing $\frac{1}{2}$ in. for the crater.

Standard conditions

As a result of numerous tests using mild steel plates,[13] the following standard conditions were adopted:

Alternating Current	170 amp
Open-circuit voltage	100 V
Length of electrode per inch of weld	2 in.
Machine speed number	6 (1·10°/sec)

These conditions were known to discriminate well between electrodes differing only slightly in their hot-cracking propensity.

Alloy Weld Metal Tests (using Mild Steel Plate)

Methods of introducing alloying elements

The effect of hot cracking of various elements was assessed by tests in which, by special techniques, the concentration of the element in the weld could be varied without affecting the concentration of other elements. It would be difficult to effect this variation by the use of alloy steel plates, since elements other than the one being studied would inevitably vary in successive casts. The techniques used were:

(i) The introduction of an element to the parent plate by a diffusion heat treatment; the weld metal is then enriched in this element by the normal process of dilution. The

concentration of the desired element is varied by altering the time of the diffusion heat treatment. This method has been used successfully for carbon, and preliminary experiments have been made with aluminium

(ii) To place a wire of the desired element in the root of the fillet before welding. The concentration of the element is varied by altering the diameter of the wire or by using more than one wire. This method was successful for nickel, and was also used with less success for copper, and (with heavily chromium-plated iron wires) for chromium. Carburized iron wires were used to introduce additional carbon into the weld metal, but it was found impossible by this means to increase the carbon content of the weld metal by more than 0·03%; method (i) was therefore preferred.

Effect of carbon

In parallel work[13, 15] it has been shown that the Mn/S ratio is an important factor in controlling the hot cracking of mild steel welds. The effect of carbon (in the range 0·06–0·30%) has now been investigated for a range of Mn/S ratios in the absence of other alloying elements, and it is possible to examine the relative importance of these factors.

Tests were carried out according to the standardized procedure, using mild steel plates previously carburized for various times (0, 1, 2 and 4 hr) at 895°C, in Kasenit No. 6 pack-carburizing medium. The electrodes were chosen so as to give a wide range of Mn/S ratios. After welding, the individual welds were broken open for the measurement of crack length, and analysis samples were taken from each.

Table I gives the analysis of each weld and the length of crack obtained, together with the plate carburizing treatment, the electrode code letter and the BS.1719 classification. The results are presented graphically in Fig. 3, where the number by each point shows the measured crack length in inches. Contour lines have been sketched which represent crack lengths from 0 to 2·5 in. at intervals of 0·5 in.

This diagram shows that carbon has an important influence on hot cracking, as assessed by Murex tests. In the range 0·06 to 0·11% C, the Mn/S ratio is the controlling factor, crack-free welds being obtained for Mn/S ratios exceeding about 22. Above 0·11% C, carbon content becomes more important, but freedom from cracking is still obtainable up to 0·125% C by increasing the Mn/S ratio to 30. With carbon contents over 0·13%, cracking is more prevalent, but high Mn/S ratio is still beneficial even at the highest level of carbon investigated. The highest carbon content for which a completely crack-free weld was obtained was 0·155%, with a Mn/S ratio of 59.

The results suggest that, in practice, welds subjected to restraint may be liable to hot cracking if the carbon content of the weld metal exceeds 0·15%. The corresponding carbon content of the plate will depend upon the dilution; the carbon derived from the electrode is usually very small, so that, assuming 50% dilution, hot cracking would be likely to occur when using plates containing more than 0·3% C.

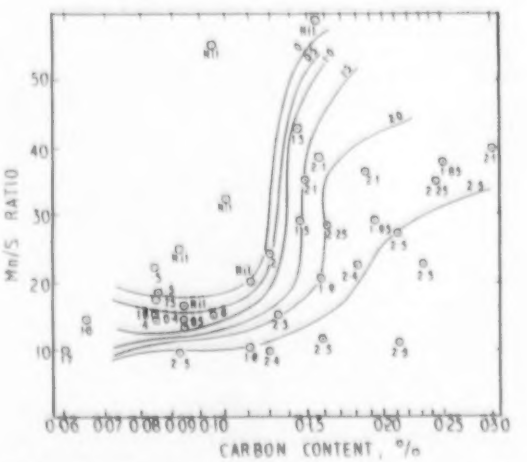
The present results are very similar to those obtained by Podgaetskii[16] who used the submerged-arc process and assessed the cracking tendency by a T-test. He

Table I

Murex hot-cracking tests using mild steel plates with and without carburizing treatments

Electrode Class	*Code*	*Carburizing time, hr*	*Crack length, in.*	*Weld metal composition* Mn, %	S, %	*Mn/S ratio*	C, %
E356	AI	nil	0·85	0·53$_5$	0·039	13·6	0·094
E356	AI	nil	0·75	0·53$_4$	0·030	17·7	0·085
E614	N	nil*	1·0	0·61	0·043	14·2	0·066
E619	AV	nil	1·8	0·55	0·038	14·5	0·085
E646	AP	nil	0·4	0·48	0·034	14·1	0·094
E646	AP	nil	nil	0·53	0·032	16·6	0·094
E616	AO	**	1·3	0·90	0·021	42·8	0·144
E319	E	**	2·4	0·34	0·035	9·7	0·130
E219	B	**	2·3	0·51	0·034	15·0	0·135
E616	AO	**	2·25	0·68	0·024	28·3	0·162
E616	AO	†	1·85	0·87	0·023	37·8	0·250
E319	E	nil	2·5	0·34	0·035	9·7	0·093
E219	B	nil	0·4	0·51	0·036	14·2	0·084
E616	AO	nil	nil	0·70	0·028	25·0	0·093
E319	E	nil	1·7	0·41$_4$	0·041	10·1	0·061
E319	E	4	2·5	0·45$_4$	0·041	11·1	0·212
E219	B	nil	0·5	0·68$_0$	0·036	18·9	0·086
E219	B	4	2·5	0·84$_1$	0·038	22·3	0·234
E614	N	nil	0·5	0·51$_4$	0·023	22·4	0·084
E614	N	4	2·5	0·65$_0$	0·024	27·1	0·211
E616	AO	nil	nil	0·89$_9$	0·028	32·1	0·111
E616	AO	4	2·25	0·91$_0$	0·026	35·0	0·243
E616	AO	nil	nil	1·13$_5$	0·020$_5$	55·2	0·105
E616	AO	4	2·1	1·08$_4$	0·027	40·2	0·301
E219	B	2	2·4	0·61$_0$	0·027	22·6	0·183
E616	AO	2	2·1	0·90$_5$	0·025	36·2	0·188
E616	AO	2	1·95	0·96$_4$	0·033	29·2	0·193
E319	E	2	2·5	0·44$_0$	0·039	11·3	0·157
E614	N	2	1·9	0·65$_3$	0·032	20·4	0·158
E319	E	1	1·8	0·42$_5$	0·041$_5$	10·2	0·121
E614	N	1	0·2	0·64	0·026$_4$	24·2	0·130
E614	N	1	0·6	0·41	0·027$_0$	15·2	0·106
E219	B	1	nil	0·60	0·030	20·0	0·122
E616	AO	1	1·5	0·90$_3$	0·031$_3$	29·0	0·147
E616	AO	1	2·1	0·92$_3$	0·026$_4$	35·0	0·150
E616	AO	1	2·1	1·10	0·028$_8$	38·4	0·158
E616	AO	1	nil	1·14	0·019$_3$	59·0	0·155

* Electrode impregnated with sulphur
** Only one of the two test plates carburized (for over 4 hr)
† Both plates heavily carburized



3—*Effect of carbon content and Mn/S ratio on severity of hot cracking in Murex test on mild steel plates*

Table II

Murex hot-cracking tests using mild steel plate with nickel wire additions

(Crack length in inches)

Wire addition		*Electrode Code and BS.1719 classification*				
Dia., in.	*Number*	*E E319*	*AP E646*	*N E614*	*AO E616*	*AQ E616*
—	none	1·4 2·0	0·5 0·45 2·2 nil, nil	nil	nil nil	nil
0·0116	1		0·45 0·35		nil 0·7	
0·0164	1	2·4 1·65	1·9 2·0 0·1	nil nil	2·0 1·8	0·1 nil
0·0164	2	2·05 2·4	2·2 1·3 1·1 0·65	0·35 0·3	1·5 1·9 0·4	nil 1·9 nil nil
0·0164	3	2·2 2·35	2·3	0·3 0·25 0·5 nil	2·15 1·6 1·9 2·4	1·9 2·0 1·9 nil, nil
0·0164	4			2·3 1·9 2·0 0·35 nil		nil nil
0·0164	6			2·2 2·2 2·4		2·1 1·7

Table III

Murex hot-cracking tests on mild steel plates with nickel wire additions

Electrode		*Ni wires added*		*Composition*			*Crack length in.*
Class	*Code*	*No.*	*Dia., in.*	Mn, %	S, %	Ni, %	
E.319	E	none	—	0·42	0·029	nil	1·4
		1	0·0164			0·40	1·65
		2	0·0164			0·88	2·05
		3	0·0164	0·39	0·027	1·26	2·2
E.646	AP	none	—	0·49	0·024	trace	0·5
		1	0·0116			0·16	0·45
		1	0·0164			0·42	2·0
		2	0·0164	0·51	0·024	0·79	2·2
E.614	N	none	—	0·62	0·020	nil	nil
		1	0·0164			0·42	nil
		2	0·0164			0·83	0·3*
		3	0·0164			1·26	0·3*
		4	0·0164			1·60	2·0
		6	0·0164	0·70	0·018	2·36	2·2
E.616	AO	none	—				nil
		1	0·0116			0·24	0·7
		1	0·0164			0·47	1·8†
		2	0·0164			0·65	1·9
		3	0·0164	0·86	0·019	0·79	2·15
E.616	AQ	none	—	1·02	0·024	trace	nil
		1	0·0164			0·40	0·1
		2	0·0164			0·63	nil
		3	0·0164	0·95	0·020	0·83	2·0

* Porous start † Porous weld

found that all welds containing 0·16% C and over were cracked, irrespective of Mn/S ratio, although he did not investigate ratios exceeding 40.

Effect of nickel

Control tests were first made with pure iron wires placed in the root of the fillet before welding. These established that the presence of a wire did not affect the severity of cracking. Preliminary experiments were then carried out using nickel wires; these indicated that calculated nickel contents of about 0·65% in the weld metal produced an increase in hot cracking when using electrode *E** (class *E*319 of the BS.1719 classification).

More extensive tests were then made, and the crack length measurements are given in Table II. The wires could be observed during welding, and a few tests in which they failed to melt uniformly and regularly were rejected. The nickel wire did not affect the arc time nor the energy input. There is a marked scatter in the results of Table II although the detrimental effect of nickel is clearly demonstrated.

Some of the welds were analysed, and their compositions and crack lengths are given in Table III. The electrodes used appear to vary considerably in their tolerance for nickel, and although there is a trend for the weld metals of high Mn/S ratio to withstand rather more nickel without cracking than those of low Mn/S ratio, the correlation is poor. Electrodes *N* and *AQ* gave the best tolerance for nickel; about 1% could be added to the weld metal without seriously increasing the severity of hot cracking.

Effect of other elements

Copper—Two Murex tests were carried out using electrode *E* and a copper wire of 0·022 in. dia.; these gave crack lengths of 1·3 and 1·1 in. The copper content of the weld which cracked to 1·3 in. was found to be 0·99%. Similar tests using the same batch of electrodes and pure iron wires gave crack lengths of 0·5 and 0·6 in., indicating that copper increases hot cracking. However, this method of inserting a wire is not very satisfactory owing to the low melting point of copper.

Chromium—A test in which 0·5 g of chromium powder was spread along the root of a fillet gave (with electrode *E*) a crack length of 0·6 in. and the weld metal was found to contain 0·83% chromium. This method of introducing chromium was not considered to be satisfactory in view of the likelihood of segregation along the length of the weld. The result suggests that chromium does not increase hot cracking, but confirmatory work is required.

Cerium—A small but undetermined quantity of mischmetall (50% cerium) introduced to a nickel-containing weld resulted in a slight improvement in resistance to hot cracking. This result was not unexpected, as it is understood that cerium additions improve the hot-tearing properties of cast steels.

Aluminium—Preliminary tests were carried out on plates calorized for 6 hr at 895°C. in the following powdered mixture:

* The electrode codes are the same as those used in a previous report.[13]

concentration of the desired element is varied by altering the time of the diffusion heat treatment. This method has been used successfully for carbon, and preliminary experiments have been made with aluminium

(ii) To place a wire of the desired element in the root of the fillet before welding. The concentration of the element is varied by altering the diameter of the wire or by using more than one wire. This method was successful for nickel, and was also used with less success for copper, and (with heavily chromium-plated iron wires) for chromium. Carburized iron wires were used to introduce additional carbon into the weld metal, but it was found impossible by this means to increase the carbon content of the weld metal by more than 0·03%; method (i) was therefore preferred.

Effect of carbon

In parallel work[13, 15] it has been shown that the Mn/S ratio is an important factor in controlling the hot cracking of mild steel welds. The effect of carbon (in the range 0·06–0·30%) has now been investigated for a range of Mn/S ratios in the absence of other alloying elements, and it is possible to examine the relative importance of these factors.

Tests were carried out according to the standardized procedure, using mild steel plates previously carburized for various times (0, 1, 2 and 4 hr) at 895°C. in Kasenit No. 6 pack-carburizing medium. The electrodes were chosen so as to give a wide range of Mn/S ratios. After welding, the individual welds were broken open for the measurement of crack length, and analysis samples were taken from each.

Table I gives the analysis of each weld and the length of crack obtained, together with the plate carburizing treatment, the electrode code letter and the BS.1719 classification. The results are presented graphically in Fig. 3, where the number by each point shows the measured crack length in inches. Contour lines have been sketched which represent crack lengths from 0 to 2·5 in. at intervals of 0·5 in.

This diagram shows that carbon has an important influence on hot cracking, as assessed by Murex tests. In the range 0·06 to 0·11% C, the Mn/S ratio is the controlling factor, crack-free welds being obtained for Mn/S ratios exceeding about 22. Above 0·11% C, carbon content becomes more important, but freedom from cracking is still obtainable up to 0·125% C by increasing the Mn/S ratio to 30. With carbon contents over 0·13%, cracking is more prevalent, but high Mn/S ratio is still beneficial even at the highest level of carbon investigated. The highest carbon content for which a completely crack-free weld was obtained was 0·155%, with a Mn/S ratio of 59.

The results suggest that, in practice, welds subjected to restraint may be liable to hot cracking if the carbon content of the weld metal exceeds 0·15%. The corresponding carbon content of the plate will depend upon the dilution; the carbon derived from the electrode is usually very small, so that, assuming 50% dilution, hot cracking would be likely to occur when using plates containing more than 0·3% C.

The present results are very similar to those obtained by Podgaetskii[16] who used the submerged-arc process and assessed the cracking tendency by a **T**-test. He

Table I

Murex hot-cracking tests using mild steel plates with and without carburizing treatments

Electrode Class	Code	*Carburizing time, hr*	*Crack length, in.*	*Weld metal composition* Mn, %	S, %	*Mn/S ratio*	C, %
E356	AI	nil	0·85	0·53$_2$	0·039	13·6	0·094
E356	AI	nil	0·75	0·53$_4$	0·030	17·7	0·085
E614	N	nil*	1·0	0·61	0·043	14·2	0·066
E619	AV	nil	1·8	0·55	0·038	14·5	0·085
E646	AP	nil	0·4	0·48	0·034	14·1	0·094
E646	AP	nil	nil	0·53	0·032	16·6	0·094
E616	AQ	**	1·3	0·90	0·021	42·8	0·144
E319	E	**	2·4	0·34	0·035	9·7	0·130
E219	B	**	2·3	0·51	0·034	15·0	0·135
E616	AO	**	2·25	0·68	0·024	28·3	0·162
E616	AQ	†	1·85	0·87	0·023	37·8	0·250
E319	E	nil	2·5	0·34	0·035	9·7	0·093
E219	B	nil	0·4	0·51	0·036	14·2	0·084
E616	AO	nil	nil	0·70	0·028	25·0	0·093
E319	E	nil	1·7	0·41$_4$	0·041	10·1	0·061
E319	E	4	2·5	0·45$_4$	0·041	11·1	0·212
E219	B	nil	0·5	0·68$_0$	0·036	18·9	0·086
E219	B	4	2·5	0·84$_7$	0·038	22·3	0·234
E614	N	nil	0·5	0·51$_4$	0·023	22·4	0·084
E614	N	4	2·5	0·65$_0$	0·024	27·1	0·211
E616	AO	nil	nil	0·89$_0$	0·028	32·1	0·111
E616	AO	4	2·25	0·91$_0$	0·026	35·0	0·243
E616	AQ	nil	nil	1·13$_3$	0·020$_5$	55·2	0·105
E616	AQ	4	2·1	1·08$_4$	0·027	40·2	0·301
E219	B	2	2·4	0·61$_0$	0·027	22·6	0·183
E616	AO	2	2·1	0·90$_5$	0·025	36·2	0·188
E616	AQ	2	1·95	0·96$_4$	0·033	29·2	0·193
E319	E	2	2·5	0·44$_0$	0·039	11·3	0·157
E614	N	2	1·9	0·65$_4$	0·032	20·4	0·158
E319	E	1	1·8	0·42$_5$	0·041$_5$	10·2	0·121
E614	N	1	0·2	0·64	0·026$_4$	24·2	0·130
E614	N	1	0·6	0·41	0·027$_0$	15·2	0·106
E219	B	1	nil	0·60	0·030	20·0	0·122
E616	AO	1	1·5	0·90$_5$	0·031$_2$	29·0	0·147
E616	AO	1	2·1	0·92$_5$	0·026$_4$	35·0	0·150
E616	AQ	1	2·1	1·10	0·028$_6$	38·4	0·158
E616	AQ	1	nil	1·14	0·019$_3$	59·0	0·155

* Electrode impregnated with sulphur
** Only one of the two test plates carburized (for over 4 hr)
† Both plates heavily carburized

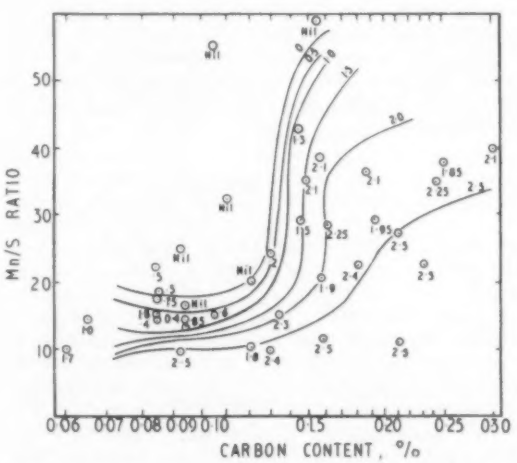


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Table II

Murex hot-cracking tests using mild steel plate with nickel wire additions

(Crack length in inches)

Wire addition		*Electrode Code and BS.1719 classification*				
Dia., in.	*Number*	*E* *E319*	*AP* *E646*	*N* *E614*	*AO* *E616*	*AQ* *E616*
—	none	1·4 2·0	0·5 0·45 2·2 nil, nil	nil	nil nil	nil
0·0116	1		0·45 0·35		nil 0·7	
0·0164	1	2·4 1·65	1·9 2·0 0·1	nil nil	2·0 1·8	0·1 nil
0·0164	2	2·05 2·4	2·2 1·3 1·1 0·65	0·35 0·3	1·5 1·9 0·4	nil 1·9 nil nil
0·0164	3	2·2 2·35	2·3	0·3 0·25 0·5 nil	2·15 1·6 1·9 2·4	1·9 2·0 1·9 nil, nil
0·0164	4			2·3 1·9 2·0 0·35 nil		nil nil
0·0164	6			2·2 2·2 2·4		2·1 1·7

Table III

Murex hot-cracking tests on mild steel plates with nickel wire additions

Electrode		*Ni wires added*		*Composition*			*Crack length*
Class	*Code*	*No.*	*Dia., in.*	Mn, %	S, %	Ni, %	*in.*
E.319	E	none	—	0·42	0·029	nil	1·4
		1	0·0164			0·40	1·65
		2	0·0164			0·88	2·05
		3	0·0164	0·39	0·027	1·26	2·2
E.646	AP	none	—	0·49	0·024	trace	0·5
		1	0·0116			0·16	0·45
		1	0·0164			0·42	2·0
		2	0·0164	0·51	0·024	0·79	2·2
E.614	N	none	—	0·62	0·020	nil	nil
		1	0·0164			0·42	nil
		2	0·0164			0·83	0·3*
		3	0·0164			1·26	0·3*
		4	0·0164			1·60	2·0
		6	0·0164	0·70	0·018	2·36	2·2
E.616	AO	none	—				nil
		1	0·0116			0·24	0·7
		1	0·0164			0·47	1·8†
		2	0·0164			0·65	1·9
		3	0·0164	0·86	0·019	0·79	2·15
E.616	AQ	none	—	1·02	0·024	trace	nil
		1	0·0164			0·40	0·1
		2	0·0164			0·63	nil
		3	0·0164	0·95	0·020	0·83	2·0

* Porous start † Porous weld

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Effect of nickel

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Effect of other elements

Copper—Two Murex tests were carried out using electrode *E* and a copper wire of 0·022 in. dia.; these gave crack lengths of 1·3 and 1·1 in. The copper content of the weld which cracked to 1·3 in. was found to be 0·99%. Similar tests using the same batch of electrodes and pure iron wires gave crack lengths of 0·5 and 0·6 in., indicating that copper increases hot cracking. However, this method of inserting a wire is not very satisfactory owing to the low melting point of copper.

Chromium—A test in which 0·5 g of chromium powder was spread along the root of a fillet gave (with electrode *E*) a crack length of 0·6 in. and the weld metal was found to contain 0·83% chromium. This method of introducing chromium was not considered to be satisfactory in view of the likelihood of segregation along the length of the weld. The result suggests that chromium does not increase hot cracking, but confirmatory work is required.

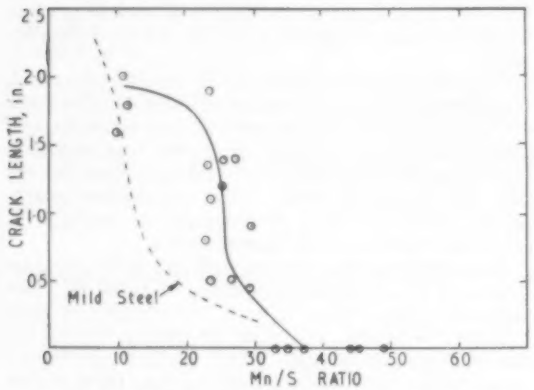
Cerium—A small but undetermined quantity of mischmetall (50% cerium) introduced to a nickel-containing weld resulted in a slight improvement in resistance to hot cracking. This result was not unexpected, as it is understood that cerium additions improve the hot-tearing properties of cast steels.

Aluminium—Preliminary tests were carried out on plates calorized for 6 hr at 895°C. in the following powdered mixture:

* The electrode codes are the same as those used in a previous report.[13]

50% aluminium-iron (50%) hardener alloy
49% alumina
1% ammonium chloride.

Table IV shows that an appreciable amount of aluminium was picked up by the weld metal, but that the aluminium content appears to vary considerably for the three classes of electrode used. There were too few tests to permit definite conclusions, but the effect of aluminium on hot cracking does not appear to be very great.



4—*Effect of Mn/S ratio on severity of hot cracking in Murex test on Fortiweld II steel (Mo–B)*

Table IV

Preliminary Murex hot-cracking tests on mild steel plates with aluminium additions

Electrode BS.1719 Class	Code	*Plate*	*Al. in weld metal, %*	*Crack length in.*
E219	B	Calorized mild steel	0·03	0·8
E219	B			0·8
E319	E		0·07	1·55
E319	E			1·3
E616	AO		0·14	nil
E616	AO			nil
E219	B	Mild steel		0·3
E319	E			1·75
E616	AO			nil
E616	AO			0·2

Table VI

Murex hot-cracking tests using Fortiweld II (Mo-B) steel

Electrode BS.1719 class	Code	*Weld metal composition, %* Mn	S	*Mn/S ratio*	*Crack length, in.*
E219	B	0·74	0·025	29·6	0·9
		0·62	0·027	22·9	0·8
					0·75
E319	E*	0·38	0·038	10·0	1·6
		0·40	0·037	10·8	2·0
		0·42	0·037	11·4	1·8
E319	E†				0·6
					0·9
E614	N	0·58	$0·022_5$	25·8	1·4
		0·68	0·025	27·2	1·4
		0·58	0·025	23·2	1·35
		0·56	0·022	25·5	1·2
		0·57	0·024	23·8	1·9
		0·59	0·025	23·6	1·1
E614	O	1·08	0·040	27·0	0·5
		1·04	0·044	23·6	0·5
		1·11	0·038	29·2	0·45
E616	AO	0·83	0·025	33·2	nil
		0·87	0·025	34·8	nil
		0·90	0·024	37·5	nil
E616	AQ	1·13	0·023	49·1	nil
		1·09	0·029	45·4	nil
		1·06	0·024	44·2	nil
E616	AQ**				nil

* Special batch † Batch 198902 ** Early batch

Table VII

Murex hot-cracking tests using steel D (Mn–Ni–Cr–Mo)

Electrode BS.1719 class	Code	*Weld metal composition, %* Mn	S	*Mn/S ratio*	*Crack length, in.*
E319	E*	$0·47_2$	$0·034_7$	13·6	0·8
		$0·49_5$	$0·034_3$	14·4	1·15
E646	AP	$0·64_0$	$0·027_4$	23·3	0·3
		$0·47_5$	$0·026_8$	17·7	nil
E614	N	$0·70_5$	$0·026_9$	26·2	0·5
		$0·73_7$	$0·021_2$	34·7	0·25
E616	AO	$1·06_0$	$0·020_8$	51·0	nil
		$1·04_0$	$0·020_8$	50·0	nil
E616	AQ	1·29	$0·020_4$	63	nil

* Special batch

Table V

Compositions of alloy and mild steel plates used in hot-cracking tests

Steel Plate Designation	*Type*	*Composition, %* C	Si	S	P	Mn	Ni	Cr	Mo	B	V	Cu
Fortiweld II	Mo–B	0·11	0·19	0·040	0·034	0·55	—	—	0·49	0·0028	—	—
D	Mn–Ni–Cr–Mo	0·16	0·22	0·039	0·016	1·05	1·13	1·02	0·31	—	—	—
Ducol W.25*	Mn–Mo	0·19	0·05	0·025	0·019	1·48	0·33	0·10	0·28	—	—	—
ID	2% Ni	0·21	0·12	0·030	0·016	0·66	2·34	0·02	—	—	—	—
E27	Ni–Cr–Mo	0·43	0·20	0·014	0·012	0·67	2·76	0·64	0·61	—	—	0·06
E27(HC)	Ni–Cr–Mo–V	0·51	0·23	—	0·014	0·55	3·30	0·71	0·65	—	0·13	—
	Mild steels	0·16 to 0·21	0·15 to 0·19	0·048 to 0·052	0·028 to 0·037	0·49 to 0·57	0·04 to 0·05	—	—	—	—	—

* Cast analysis

Table VIII

Murex hot-cracking tests using Ducol W25 (Mn–Mo) steel

Electrode		*Weld metal composition, %*		*Mn/S ratio*	*Crack length, in.*
BS.1719 class	*Code*	Mn	S		
E319	E*	0·47	0·038	12·4	0·9
		0·42	0·038	11·1	1·5
		0·43	0·038	11·3	1·5
E319	E†				nil
					0·4
E614	N	0·61	0·019	32·1	0·7
		0·66	0·026	25·4	nil
		0·66	0·023	28·7	0·3
E614	O	1·18	0·037	31·9	0·4
		1·15	0·032	35·9	0·2
		1·13	0·036	31·4	0·3
E616	AO	0·92	0·026	35·4	nil
		0·99	0·024	41·2	0·4
		0·99	0·023	43·0	0·4
E646	AP				nil
E616	AQ	1·21	0·020	60·5	nil
		1·15	0·017	67·6	nil
		1·23	0·026	47·2	nil
E616	AQ**				nil
					0·3

* Special batch † Batch 198902 ** Early batch

Table IX

Murex hot-cracking tests using E27 (HC) steel (3% Ni–Cr–Mo–V, high carbon)

Electrode		*Weld metal composition, %*		*Mn/S ratio*	*Crack length, in.*
BS.1719 class	*Code*	Mn	S		
E319	E*	0·36	0·032	11·3	2·0
		0·38	0·026	14·6	1·5
		0·38	0·036	10·6	2·2
E614	N	0·52	0·016	32·5	nil
		0·59	0·024	24·6	0·1
		0·56	0·021	26·6	2·0
E614	O	0·99	0·025	39·6	2·25
		0·95	0·037	25·7	2·3
		0·99	0·028	35·4	2·3
E616	AO	0·78	0·015	52·0	1·7
		0·78	0·017	45·9	2·1
E616	AQ	0·92	0·017	54·1	2·0
		0·89	0·014	63·6	1·8
		0·82	0·016	51·2	2·0

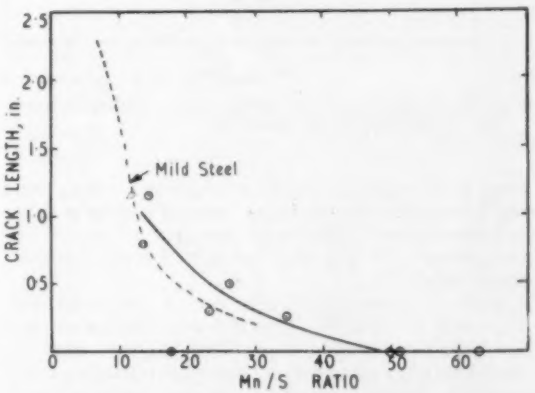
* Special batch

Table X

Murex hot-cracking tests using steel E27 (Ni–Cr–Mo) and ID (2% Ni)

Plate	*Electrode*		*Crack length, in.*
	BS.1719 class	*Code*	
E27	E219	B	1·85
	E646	AP	2·3
	E616	AQ *	1·75
ID	E319	E†	0·3
			nil

* Early batch † Batch 198902



5—Effect of Mn/S ratio on severity of hot cracking in Murex test on steel D (Mn–Ni–Cr–V)

Tests Using Alloy Steel Plate

The compositions of the alloy steel plates used are given in Table V, together with the range of composition for the mild steels used in comparative tests.

Tables VI–X contain the detailed results of crack length measurements for each alloy steel, and also the manganese and sulphur contents determined on most of the weld metals.

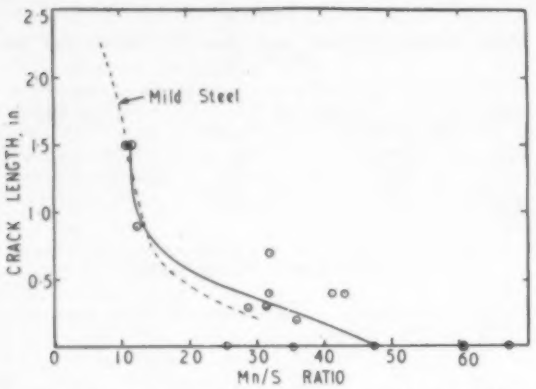
The hot-cracking propensities of the steels may be readily compared by examining the summarized results in Table XI, which also includes typical results for mild steels of the compositions given in Table V. When using a given electrode, Ducol *W*.25

Table XI

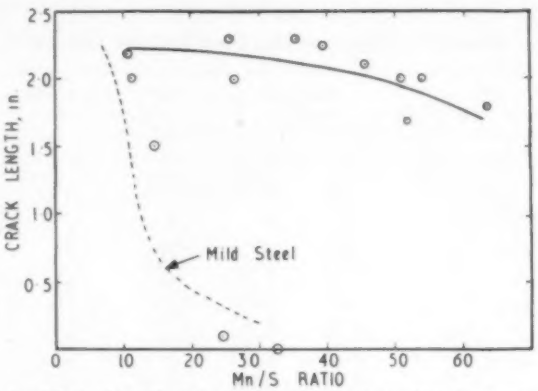
Summary of hot-cracking test results for alloy and mild steel plates

Steel Plate		*Mean crack length (in.) for the following electrodes (Code and BS.1719 classification)*								
Designation	*Type*	*B E219*	*E* E319*	*E† E319*	*N E614*	*O E614*	*AO E616*	*AQ E616*	*AQ** E616*	*AP E646*
Fortiweld II	Mo–	0·8 (3)	1·8 (3)	0·75 (2)	1·4 (6)	0·5 (3)	nil (3)	nil (3)	nil (1)	
D	Mn–Ni–Cr–Mo		1·0 (2)		0·4 (2)		nil (2)	nil (1)		0·15 (2)
Ducol W.24	Mn–Mo		1·3 (3)	0·2 (2)	0·3 (3)	0·3 (3)	0·3 (3)	nil (3)	0·15 (2)	nil (1)
ID	2% Ni			0·15 (2)						
E27	Ni–Cr–Mo	1·85 (1)							1·75 (1)	2·3 (1)
E28(HC)	Ni–Cr–Mo–V		1·9 (3)	2·0 (1)§		2·3 (3)	1·9 (2)	1·9 (3)		
	Mild steels	0·3 (2)	1·5 (3)	0·6 (2)	0·45 (2)	0·25 (2)	0·15 (2)	nil (2)		0·65 (2)

Figures in parentheses denote the number of test results
* Special batch † Batch 198902 § Also nil (1) and 0·1 (1) ** Early batch



6—*Effect of Mn/S ratio on severity of hot cracking in Murex test on Ducol W.25 steel (Mn-Mo)*



7—*Effect of Mn/S ratio on severity of hot cracking in Murex test on E.27(HC) steel (Ni–Cr–Mo–V)*

steel gives slightly shorter crack lengths than mild steel, probably because of its high manganese and low sulphur content. The small amounts of nickel and molybdenum in this steel seem to have a relatively minor effect.

Steel *D*, which, in addition to 0·31% Mo, contains 1% each of Mn, Ni, and Cr also compares very favourably with mild steel. This suggests that the beneficial high manganese content has outweighed any possible detrimental effect of the other alloying elements.

For Fortiweld II steel (Mo–B), cracking was slightly more severe than in mild steel, possibly indicating that boron increases the tendency to hot cracking.

Steels *E*.27 and *E*.27(HC) (Ni–Cr–Mo and Ni–Cr–Mo–V) show severe hot cracking, which may be due to their higher carbon contents; it is not possible to make any deductions regarding the effect of the other alloying elements.

Limited tests on steel *ID*, which contains over 2% Ni, show that this also compares favourably with mild steel, suggesting that the effect of differences in manganese and sulphur are sufficient to outweigh the detrimental effect of nickel (already shown by wire additions).

In Figs. 4–7, crack lengths have been plotted against weld metal Mn/S ratio for four steels. A curve for mild steel, taken from previous work[15] has been included for comparison. This presentation permits the steels to be compared under conditions of constant Mn/S ratio in the weld. This may be misleading if an appraisal of the hot-cracking propensities of the steels is required, but it enables conclusions to be drawn regarding the effects of elements other than sulphur and manganese. Ducol *W*.25 and steel *D* have almost identical curves. The compositions are similar except that steel *D* contains approximately 1% each of nickel and chromium. Three alternative deductions may be made from a comparison of these two steels:

(i) Both nickel and chromium have an almost negligible effect on hot cracking
(ii) The detrimental effect of nickel is balanced by the beneficial effect of chromium in steel *D*
(iii) The detrimental effect of chromium is balanced by the beneficial effect of nickel (again in steel *D*)

Since nickel has already been shown to increase hot cracking, deduction (ii) appears to be the most likely, and it follows that chromium is beneficial.

Steel *E*.27(HC) gives severe cracking, which is diminished only slightly with increasing Mn/S ratio. This steel is high in carbon and nickel, and it seems likely that the principal cause of the severe cracking is the high carbon content.

Effect of Preheat

Preheating is frequently adopted as a means of avoiding cold cracking in the weld metal, or in the heat-affected zone, owing to the presence of hydrogen. In consequence, it was thought desirable to determine the effect of preheating on hot cracking.

Preheating may be expected to influence cracking at high temperatures in several ways. Firstly, by diminishing the thermal gradients it may reduce the stresses which the weld is required to withstand and thus be beneficial. Secondly, by decreasing the rate of cooling, it will increase the time at which the weld metal is at high temperatures,* and if the weld metal is hot-short, cracking may be increased. Thirdly, as pointed out by Medovar,[17] retardation of crystallization rate results in increased diffusion, which should reduce dendritic segregation, and consequently increase the temperature of complete solidification and reduce cracking. For low preheat temperatures (up to 250°C.), Murex hot-cracking tests show that there is no effect. Since the test applies restraint by a positive relative movement of the two test plates, preheating would not diminish this restraint as it might be expected to in a practical weld, and therefore the test would be expected to emphasize any detrimental effect of preheating.

Tests were carried out as already described, using steel *D* (Mn–Ni–Cr–Mo) and five electrodes chosen to give a wide range of Mn/S ratios in the weld metals. The plates were preheated (in a forced air circulation furnace) and tests were carried out successively at room temperature, 100°, 175° and 250°C. Tests under standard conditions could not be made at temperatures above 250°C. owing to excessive melting of the plate.

* This effect may be negligible.

Table XII

Crack lengths (in.) for various preheat temperatures
(Murex hot-cracking test and Mn–Ni–Cr–Mo steel D)

Electrode		*Preheating temperature, °C.*							
Class	*Code*	*Room*		*100*		*175*		*250*	
E319	E	0·8	1·15	1·75	0·95	1·0		0·9	(1·1)
E646	AP	0·3	nil	0·25	0·45	0·5	0·4	(0·4)	(0·35)
E614	N	0·5	0·25	0·4	0·45	0·45	0·45	nil	0·2
E616	AO	nil	nil	nil	0·2	nil	0·3	0·2	nil
E616	AQ	nil		nil	nil	0·35	nil	nil	nil

The measurements in parentheses refer to tests in which there was a small departure from standard conditions

Table XIII

Murex hot-cracking tests for welds of different sizes on mild steel

Electrode		*Gauge, s.w.g.*	*Current, amp*	*Arc time, sec*	*Electrode length, in.*	*Arc energy kJ/in.*	*Equivalent fillet leg length, in.*	*Crack length, in.*
		8	170	41·6	6·0	47·0	0·34	1·75
		8	158	40·5	5·4	40·4	0·30	1·7
		8	149	38·6	4·8	35·4	0·27	1·4
		10	118	41·5	6·0	31·1	0·26	1·3
E319	E	10	118	41·0	6·15	31·3	0·26	1·7
		6	192	39·0	4·4	45·6	0·33	1·9
		6*	215	41·8*	5·0	54·1	0·37	1·7
		6	209	46·1	5·4	60·0	0·40	1·4
		6	210	34	4·1	43·0	0·31	1·4
		8	169	42·2	5·95	46·3	0·33	nil
E616	AO	6	205	32·5	4·15	46·6	0·33	0·1†
		10	120	39·3	5·4	29·0	0·24	0·3†
		10	120	47·8	6·9	36·7	0·28	nil
		8	170	37·2	6·0	46·6	0·33	0·5†
		8	150	37·8	5·5	37·9	0·29	0·7†
E614	N	8	150	40·7	5·8	42·2	0·31	0·4†
		8	180	37·8	6·3	45·8	0·33	0·5†
		8	180	40·9	6·9	50·8	0·36	0·5†

* Machine speed 7 (all other tests at speed 6) † Porous start

Individual crack measurements are given in Table XII. For the reported crack lengths of 0·2 to 0·5 in., there was generally some porosity at the start of the weld.

It appears that preheating to slightly elevated temperatures had no significant effect upon crack length. It can also be inferred that preheating had no effect upon the striking or starting porosity which was encountered with the basic (low hydrogen) electrodes.

Effect of Weld Size

Murex hot-cracking tests were made with welds of different sizes, obtained by varying the gauge and length of electrode deposited. The burn-off rate was controlled by varying the current.

Three brands of electrodes were used; two of these were available in different gauges which had been covered with the same batch of flux, and had similar core wire composition. The arc time was kept as constant as possible and the crack length results for the different sizes of welds should therefore be comparable.

The results of eighteen tests are given in Table XIII. They are placed in order of the arc energy per inch of weld, which has been shown by Bradstreet[18] to be directly proportional to the leg length of fillet welds.

This Table shows that for each of the three electrodes, the crack lengths do not vary appreciably with weld size. In practice, it has been observed[6] that hot cracking is worse with large diameter electrodes, possibly because they are commonly used to weld thicker sections and the conditions of restraint upon the weld may be more severe.

Discussion and Conclusions

Effects of steel composition

1. In view of the beneficial effect of high Mn/S ratio, there are advantages to be gained by keeping the sulphur content as low as possible. This applies particularly if, for any reason, it is desired to limit the manganese content. High Mn/S ratio permits the presence of the maximum amount of those useful alloying elements which increase hot cracking, without exceeding a given level of hot-cracking susceptibility.
2. Manganese, in amounts of the order of 1%, exercises a beneficial effect on the resistance to hot cracking of low alloy steels.

3. Carbon increases hot cracking, and when steels of relatively high carbon content (0·3% and over) are welded under restraint, it appears advisable to limit the dilution to ensure that the carbon content of the weld metal does not exceed about 0·15%.
4. Nickel increases hot cracking, but relatively large amounts (about 1% in the weld metal) may be tolerated without serious cracking provided that a class 6 electrode, giving a high Mn/S ratio in the weld metal, is chosen. Steels containing less than 2% nickel would not be expected to give rise to hot cracking due to this element, provided that reasonable precautions were taken.
5. Insufficient tests have been carried out to confirm the inference that chromium is beneficial to hot cracking, and may possibly counteract the harmful effect of nickel.
6. An indication has been obtained that copper, in amounts of the order of 1% in the weld metal, increase hot cracking. This large amount is not likely to be found in low alloy steel weld metals.
7. An indication has been obtained that mischmetall (50% cerium) may reduce hot cracking.

The composition of the weld metal is most important so far as hot cracking is concerned, and freedom from cracking is more likely if the dilution can be kept sufficiently low to avoid an undue concentration of deleterious elements.

Effects of electrode type

From the present investigation and parallel work on mild steel,[13] it is clear that maximum resistance to hot cracking is afforded by electrodes which give a high Mn/S ratio in the weld metal. These are all of the basic-covered, low-hydrogen type (class 6, BS.1719). Considerable differences can be obtained between the Mn/S ratios for different brands of electrodes, and one giving a ratio exceeding 35 is to be preferred.

Preheating and weld size

Preheating is often applied to lower the cooling rate of a weld so as to obtain freedom from cracking in the heat-affected zone and also to give freedom from fissuring. It has been shown that moderate preheats (up to 250°C.) do not materially influence the severity of hot cracking. In consequence, if preheating is specified to give freedom from heat-affected zone cracking, the treatment may be applied without fear of promoting hot cracking.

Small variations in weld size (using 6, 8, and 10 s.w.g. electrodes) have been shown to have no effect on hot cracking in the Murex test. This is an indication that, if a large diameter electrode is required to obtain a low cooling rate, it is unlikely that the risk of hot cracking will be seriously increased. This conclusion is tentative only, since the electrode diameter may, in practice, alter the stress system imposed on the weld. Such differences would not be apparent in the Murex test.

Specification to ensure freedom from hot cracking

It is clear that hot cracking may occur under conditions which are safe against heat-affected zone cracking, for hot cracking depends on the composition of the weld metal, and cold cracking depends on the composition and cooling rate of the heat-affected zone. The two defects are likely to be related only in their severity in as much as the composition of the parent plate affects the composition of the weld metal, owing to dilution. Consequently, it would be safer to specify a separate test to ensure freedom from hot cracking.

It is difficult to specify a hot-cracking test, since little is yet known about the degree of restraint which is imposed upon practical welds during cooling. The resistance of weld metal to restraint conditions has already been partly evaluated, and has been shown to be largely a function of the weld metal composition. The simplest method of ensuring a low risk of hot cracking is, therefore, to prescribe limits for the various elements which promote or mitigate the defect. Tentative limits may be prescribed for elements which have been adequately investigated. These are as follows:

Sulphur	0·035%	max.	Weld metal analysis
Manganese	0·80%	min.	
Manganese/sulphur ration	35	min.	
Nickel	1·0%	max.	
Carbon	0·15%	max.	

It is apparent that these contents set an upper limit to the alloy composition of the parent plate; such a limit is not imposed by considerations of heat-affected zone cracking as this defect may be avoided by employing a sufficiently slow rate of cooling. No corresponding method of preventing hot cracking has yet been found, so that it is possible that, in the future, the problem of hot cracking may assume greater practical significance than at present.

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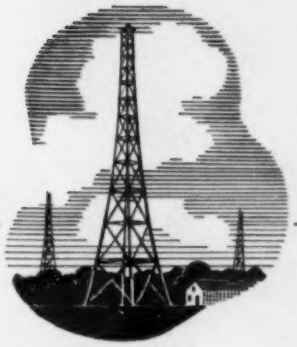

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INSTITUTE ACTIVITIES

MEETINGS

Conference on the Training and Testing of Welders

Because of unforeseen circumstances it has been decided that the Conference arranged to be held on 17th and 18th September 1959, at the offices of the Institute, shall be postponed.

A further announcement will be made as soon as a definite date has been fixed.

Spring Meeting 1960

The Institute's Spring Meeting for 1960 will be held at Ashorne Hill, near Leamington Spa, in May.

The overall theme is to be Recent Developments in Welding Processes and Their Applications. Definitive dates and further particulars will be announced as soon as possible.

Closing of Library

The Institute's Library will be closed throughout the month of August for reorganization. Queries and applications for loans received during that period will not be answered until the first week of September.

Members who have books on loan are asked to ensure that they are returned to the Library before the end of July.

APPEAL TO INDUSTRY

The following list records subscriptions received, up to the end of March, since the publication of the last list in the December 1958 issue of the *Journal* (p.576).

Donation

£52 10*s*. Aluminium Development Association.

Commonwealth Welding Conference Guarantee Fund

The following have given the sums named, which were returnable to them as Guarantors of the Conference.

£39 16*s*. 4*d*. The General Electric Co. Ltd. £10 or under. Anglo-Swedish Electric Welding Co. Ltd.; Henry Hartley & Co. Ltd.; Invicta Electrodes Ltd.; Mechans Ltd.; Samuel Osborn & Co. Ltd.; Richmond Welding Co. Ltd.; W. H. Silvester Ltd.

The total sum given or promised by the end of March 1959 is £9,262, made up of £5,932 Donations, £922 transferred from the Commonwealth Conference Fund, and £2,408 from the value of Annual Subscriptions over seven years.

NEWS OF MEMBERS

W. Barr, O.B.E., has been elected President of The Iron and Steel Institute for 1959/60.

Obituary

The Council regret to record the deaths of:

Sir William J. Larke, K.B.E., Honorary Fellow and Past-President of the Institute, a memoir of whom appears on p. 247 of this issue, on 29th April, aged 84.

The funeral service took place at St. John's Church, Sidcup, and was followed by cremation at Eltham on 4th May. Canon C. E. Webb officiated, assisted by the Rev. E. E. Turner.

The Institute was represented by Mr. E. Seymour-Semper, Vice-President, and by the Secretary, Mr. G. Parsloe. The British Welding Research Association was represented by Sir Charles Lillicrap, K.C.B., M.B.E., President.

Frank Brown, Chairman and Managing Director of The Finnieston Engineering Co. Ltd. (West of Scotland Branch – Member 1945).

BRANCH NEWS—Reports of Meetings

East Midlands — Diesel Engine Frames

On Friday, 13th March, the Branch held a joint meeting with the Lincoln Engineering Society, at the Technical College, Lincoln, when a paper on the "Design and Fabrication of Diesel Engine Frames" was presented by Mr. S. Cooper.

Mr. Cooper gave a general description of 1000 and 2000 h.p. engines, and stated that weight ratio was the first consideration for marine use, where the cost of fabrication by welding as opposed to the use of castings was not important.

As much fabrication as possible is done in sub-assembly form, and then the components are brought together for final welding. Control of distortion was achieved by trial and error until a successful welding sequence had been developed.

In the latest type of engine, castings are used for the main bearing housings, and butt welds are so placed that they are outside the explosive load area.

K.H.E.

Annual General Meeting

The Annual General Meeting of the East Midlands Branch was held at the Welbeck Hotel, Nottingham, on 7th April.

Mr. H. L. Palmer accepted the Branch Presidency for a second year, and the Branch Chairman, Mr. K. H. Ewen, was re-elected for the 1959–60 session.

At the end of the meeting two films were shown. The first was "The Vital Link", showing the manufacture of solders and brazing spelters; the second was entitled "Boring at Sea", and showed the fabrication of a tubular boring rig for coal prospecting under the sea.

K.H.E.

Manchester — Annual General Meeting

The Annual General Meeting of the Manchester and District Branch was held in Manchester on 1st April.

The meeting was opened by the Chairman, Mr. R. D. Watson, who called on the Treasurer, Mr. J. T. Tatchell, and the Secretary, Mr. E. H. Lee, to present their reports. The Treasurer went into details of Branch expenditure and reported a satisfactory balance of cash in hand at the end of the year.

The Secretary reported that the membership of the Branch had now risen to 338 of all grades. Nine meetings had been held in the year, and the average attendance for each meeting was 58 members and visitors; the actual figures were probably higher than this, for many people omitted to sign the attendance book. The Branch Dinner, at which 200 members and friends were present, had been, in the opinion of all those consulted, an unqualified success.

The Branch Committee had collaborated with the Manchester Federation of Scientific

Speakers at the Manchester Branch Dinner. (Left to right): J. Strong (President of the Institute); R. D. Watson (Branch Chairman); The Lord Mayor of Manchester; T. Storey; A. C. Main; Professor H. Wright Baker.

Societies in organizing a Conversazione and Exhibition on "Heat", at the College of Science and Technology, early in the year. As well as arranging to provide a number of the exhibits, members of the Committee acted as stewards at the exhibition.

In support of the Institute's recruiting drive, two special meetings had been organized to attract non-members. The first was held at Bolton on 13th October 1958, and the second in Manchester on 17th November. This latter meeting was particularly successful, attracting 80 non-members in a total attendance of 107.

The Chairman announced that the new Committee for the 1959–60 session would be:

Chairman, J. M. Whitworth
Vice-Chairman and Secretary, E. H. Lee
Asst. Secretary, A. C. White
Treasurer, J. T. Tatchell

Committee

J. W. Addie	A. C. Mansell
G. Bagley	A. E. G. Rice
T. Hill	S. Wilde
W. L. McIvor	R. D. Watson (*ex officio*)

The retiring Chairman made a short speech, in which he thanked the various members of the Committee for their support during the year, and afterwards invested the new Chairman with the badge of office.

The meeting closed with the showing of two interesting films, one dealing with the manufacture of glass, produced by Pilkington Bros. Ltd., and the other, a Mobiloil production, illustrating the building of Coryton Refinery.

Annual Dinner

The Annual Branch Dinner was held on 9th March at the Grand Hotel, Manchester. Among the 200 members and guests present were The Lord Mayor of Manchester, Alderman James E. Fitzsimons, J.P., and the President of the Institute of Welding, John Strong, M.A. After the loyal toasts had been proposed by the Chairman, Mr. R. D. Watson, a toast to "The City and Ports of Manchester" was proposed by Mr. T. Storey, Chairman and Managing Director of T. Storey (Engineers) Ltd. He paid tribute to those Manchester pioneers who were responsible for creating the Port of Manchester by building the Manchester Ship Canal. The Lord Mayor responded, and ended a most amusing speech with a very serious plea for a better turn-out at Local Government elections.

The toast to "The Institute and the Branch" was proposed by A. C. Main, B.E., M.I.Mech.E., M.I.E.E., Director of Manufacture of Metropolitan-Vickers Electrical Co. Ltd. Whilst pointing out that the work done by the Institute was wide in its scope and very considerable, Mr. Main emphasised that the tempo must be increased to meet the severe competition that British industry is suffering, and will continue to suffer, from overseas manufacturers.

The President of the Institute responded, and gave members some interesting and up-to-date information on the various activities of the Institute.

The Chairman, Mr. Watson, proposed a toast to "Visitors and Kindred Associations". After welcoming the visitors he said how sorry he was to learn of the indisposition of the Secretary of the Institute, Mr. Parsloe, who, after travelling up to Manchester, was unfortunately not well enough to attend the Dinner.

Professor H. Wright Baker, B.Sc., M.I.Mech.E., Head of the Mechanical Engineering Department of the Manchester College of Science and Technology, responded to the toast, and thanked the Chairman most heartily for his invitation to the Dinner.

Members and visitors alike unanimously agreed that this had been a most enjoyable and successful evening.

J.M.W.

South London — Welding in Nuclear Engineering

The last full meeting of the session was held on 16th April, when Mr. H. E. Dixon of Atomic Power Constructions Ltd. presented some of his personal views on the metallurgical considerations in welding for nuclear power applications. Since the general applications of welding in this field had been covered recently in the Annual Lecture presented to the Institute by Sir Leonard Owen, Mr. Dixon intended to review only a few specific aspects.

For this purpose he dealt with the materials, welding, and inspection of a hypothetical reactor requiring, say, a 60–70 ft dia. pressure vessel in 3–4 in. thick plate, and producing about 200–250 MW of electrical power.

In the selection of suitable materials the most important considerations were dimensional stability, notch ductility, and weldability, and these were closely tied to design and operating conditions. Resistance to creep was a vital feature, for there could be as many as 300 openings in a vessel for the connection of ducts, piping, and so on which demanded a high degree of stability.

Acceptable creep rates of 0·2% in 100–200 thousand hours had been quoted, but these were based on the extrapolation of the results of relatively short-term tests; there was a great need for long-term creep data. Likewise, there was a need for similar information on notch ductility, especially under the effects of irradiation, which could raise the transition temperature of steels by as much as 80°. Good notch toughness in the steels used for containment vessels was a prime factor in design, for no possibility of a disastrous brittle failure could be accepted, either in erection or during operation.

In regard to weldability the problems had increased because of the desire to raise operating pressures, and therefore greater thicknesses of plate had to be welded. Increases in the working stresses by the use of alloy steels was no answer, for the welding problems then became more difficult. In most instances a 0·15/0·2% C–1·0/1·5% Mn steel was chosen, either aluminium or silicon killed. Preheat at about 100°–125°C. was usually advisable and the electrodes used are preferably of the basic low-hydrogen type to avoid the possibility of microfissures, which could not be detected on inspection.

Although all welding, both in the shops and at site, had to be carried out to a strict schedule it was generally found necessary to allow considerable tolerances in the welding procedure, so as to provide for the many variations in plate edge preparation and fit-up that were inevitable.

Forgings were often used for fittings and the like, and it had been found that electric furnace steel provided adequate weldability if the sulphur and phosphorus were kept slightly lower than in the plate material with manganese slightly higher. So that there should be good ductility in the welded joint most welding was done with 10, 8, and 6 s.w.g. electrodes; a typical butt weld in 3½ in. plate, using two operators, could take up to 12 hours per foot to complete. It had not yet been found possible to use automatic welding to any extent on spherical vessels.

Mr. Dixon then reviewed some of the searching inspection procedures needed for these vessels. These covered normal mechanical tests on the material, together with Charpy **V**-notch tests. An acceptable value was 25 ft.lb at −10°C. All plates were also examined ultrasonically for laminations. There was careful control over plate edge preparation, so as to avoid distortion from poor fit-up. Electrodes were always dried before use, and there was constant testing of the welding operators.

With the present plate thicknesses of 3½ in. and over 400 kV X-ray equipment was working to its capacity and it was not easy to detect all serious faults. The use of cobalt-60 sources gave better results, but it was hoped that linear accelerators would be available for commercial use before thicknesses became too great for X-ray examination.

It was a requirement of the authorities that vessels should be stress relieved after welding to remove internal stresses. For these large vessels the best method was by the use of radiant heat inside the vessel, but this was not an easy matter.

Mr. Dixon also had some comments to make on the difficulties of proof testing, on which there was a good deal of discussion and argument at present. In the little time left at the end of his lecture he was able to touch upon only a few of the possible future trends in nuclear power design; the use of banded and reinforced vessels, and of laminated construction to avoid the need for thick plates; and improved methods of testing and inspection. He did not consider that there would be any major changes in the materials at present used.

The paper covered so much interesting ground that discussion had to be curtailed to give time for the Annual General Meeting that followed. Subjects ranged from effects of irradiation, and the types of defects that could be allowed, to the use of automatic welding for shop and site welding of seams. A vote of thanks to the speaker was proposed by Mr. Moore and was endorsed with acclamation.

BRITISH WELDING RESEARCH ASSOCIATION

Translations from the Russian

As announced recently in the Journal, the British Welding Research Association has undertaken a cover-to-cover translation in the scheme sponsored by the Department of Scientific and Industrial Research. The full contents of the periodical *Avtomaticheskaya Svarka* are being made available in English as *Automatic Welding*. The contents of the January and February issues were given last month in this section, but in future the titles will be listed with other periodicals in the section "Current Welding Literature", where this month the contents of the March issue are given.

The January translation was made available on 1st May, since the Russian version arrived in Britain only in mid-March; but the next two issues came within five weeks, so that some reduction in the gap between the dates of the Russian and English versions may perhaps be expected.

A second cover-to-cover translation, *Welding Production*, of the journal *Svarochnoe Proizvodstvo* will shortly be started by the Research Association, and this is also sponsored by DSIR. Unlike the other journal, which comes from the Ukraine, this is published in Moscow by Mashgiz, important publishers of engineering books and periodicals.

The annual subscription is expected to be £5 5*s*. for the twelve yearly issues. This journal is rather more concerned with industry and less with research than is *Automatic Welding*, and it should have a wide appeal. No date can yet be given for the publication of the first number, but it will probably be the Russian April issue.

COURSES AND MEETINGS

Welding for Teachers of Engineering

The Manchester College of Science and Technology is organizing, from 20th to 24th July 1959, a Refresher Course in Welding for technical college teachers of engineering up to Higher National Certificate level.

As well as two works visits, and an evening Brains Trust organized by the Manchester and District Branch of the Institute of Welding, there will be lectures by well known experts on the following subjects:

Fusion welding processes; Resistance Welding; Prefabrication and site assembly; Welding Metallurgy; Design of welded structures; Control of residual stresses; Design of welded connections subjected to fatigue loading; Design of welded connections subjected to static loading; Inspection and testing.

The organizing lecturer for the Course is Dr. F. Koenigsberger, from whom full particulars can be obtained at the Manchester College of Science and Technology, Sackville Street, Manchester 1.

International Exhibition of Welding Technology

In connection with the Annual Assembly of the International Institute of Welding, which is being held at Opatija, Yugoslavia, from 28th June to 4th July 1959, there is to be an International Exhibition of Welding Technology in Ljubljana, from 7th to 12th July.

It is being organized by the Institute of Welding LRS, Ljubljana, under the sponsorship of Franc Leskošek, Vice-President of the Federal People's Assembly of Yugoslavia.

The aim of the Exhibition is to show mainly advances in the automization of welding and allied techniques. These are intended to embrace the welding of metals, metal spraying, welding of plastics adhesive bonding of metals. There will also be lectures on welding and allied processes, technical films, and exhibits of international welding literature.

NEWS FROM INDUSTRY

Aluminium for Railway Rolling Stock

Locomotive engineers paid a visit to the Research Laboratories of The British Aluminium Co. Ltd., at Gerrards Cross, on 15th–16th April, with the particular object of seeing how aluminium alloys are being increasingly applied in the field of rail transport.

Since railway coaches, wagons, and under-frames can be expected to receive many reversals of loading in operation, the fatigue strengths of the alloys used, and the effects of welding on fatigue life, are primary considerations. Visitors saw the great amount of testing and investigation that is in progress on this subject at the Laboratories, and were given much information on the most suitable forms of welded joint. Tests are carried out not only on small butt and fillet welded specimens but by resonance techniques on larger built-up components—shafts, box sections, and the like. Butt welds in NP.5/6 plate give fatigue strengths (50×10^6) cycles of about 45% of the as-received unwelded material, but if the reinforcement is removed the strength increases to about 70%, or much the same as that of the unwelded annealed metal.

Experience at British Aluminium, which is supported by complimentary work at the B.W.R.A. laboratories, indicates that the method of spot heating, developed by Professor Puchner, has a considerable influence on the improvement of the fatigue life of certain built-up components. The technique is simple once the precise positions of the spots have been determined, but much more work is needed before the method can be safely applied to more complex welded constructions.

Great interest was shown in the various types of equipment available for welding the aluminium alloys, with special attention to the inert-gas processes. The tungsten arc is widely used for high-quality work on sheet, whilst the consumable electrode metal-arc process is generally used for the thicker materials. However, the Research Laboratories have been experimenting with the use of smaller wires so as to be able to weld the thinner materials by this process. A prototype gun was demonstrated as well as a commercial American model which is now being marketed in Britain (the Rowen-Arc; see *BWJ*, May, p. 242).

Although much of the welding of aluminium alloys is done manually, greater lengths of joint call for some degree of mechanization. This is being met by the development of automatic and semi-automatic equipment, based on the inert-gas process, some of which was shown and demonstrated. Much of the information on the inert-gas welding process available to the locomotive engineers at this visit is included in a booklet "Self-adjusting arc welding of aluminium and its alloys" (L.8), which has just been published by The British Aluminium Company Ltd.

NEW EQUIPMENT

Bench Model Spot Welder

Triangle Products Ltd. are now marketing at a competitive price a 7·5 kVA precision spot welder for general purpose welding. The machine incorporates a built-in electronic timer with infinitely variable adjustment from 5 to 75 cycles, and with a 'free-time' position for special conditions. When the preliminary setting is satisfactorily determined the welding cycle is then automatic.

Foil in mild steel or stainless steel as thin as 0·003 in. or sheet up to 16 s.w.g. can be welded on a continuous production basis. A throat of 6¼ in. is standard but alternative arms for a 12¼ in. reach are available.

Gas Torch for High-Temperature Welding

A gas/air torch providing a small diameter, highly concentrated flame, ideal for

precision welding of aluminium, silver soldering of copper, and for brazing, has been introduced by Sunvic Controls Ltd. The torch uses coal gas at normal mains pressure. A preheater raises the temperature of the gas and the primary air to 750°C. before they reach the mixing chamber. With this method the flame cannot be extinguished even when the torch is played into an inert atmosphere. The inner portion of the flame has a temperature greater than 2000°C. and is about 4–5 cm long.

When the torch is used for silver soldering of stainless steel there is a noticeable reduction in distortion. It has been applied successfully to the soldering and brazing of high magnesium alloys and for the autogenous welding of brass, aluminium and aluminium-magnesium alloys.

Twin Fillet Welding

The Esab A6.DK automatic arc-welding machine is now available in Britain through Welding Supplies Ltd. It has been developed specifically to provide a relatively light-weight twin fillet welding machine for operation in shipyards.

The complete unit, without the wire and flux, weighs just under 3 cwt. Twin welding heads operating a submerged-arc process are mounted on a carriage that straddles the work; they can deposit fillets on both sides of a vertical plate at speeds up to 24 in./min.

Diesel Generator of New Design

A new welding power source, called the Rockweld Type PBB.375 diesel welder, has been introduced by Rockweld Ltd. The engine is the latest Petters 4-cylinder air-cooled unit running at 3000 r.p.m. and equipped with electric starting as a standard feature. The generator, which is close-coupled to the engine, has a simple field system and coil arrangement. Current control is stepless and is provided by a single graduated hand wheel.

The current range is from 35 to a maximum of 375 amp at 25/40 arc volts, with an open circuit voltage of 65/70. The maximum continuous manual welding current is rated at 325 amp (BS.638) and under the NEMA specification the set has a rating at 40 V of 300 amp at 60% duty cycle, and 375 amp at 35% duty cycle.

The set can be supplied for road towing or for hand towing.

Electro-Slag Welding

The O.K. Organization, whose British representatives are Welding Supplies Ltd., have secured rights to manufacture and market the equipment for electro-slag welding, as developed at the Paton Institute of Electric Welding in Kiev, Russia.

Two sizes of machines will be made. One is capable of welding materials from 2½ to 24 in. thick and the other is designed to deal with thicknesses between 1½ and 4 in. These should cover most of the needs for welding pressure vessels and steel castings in the shipbuilding and heavy machine industries.

Tray Loading Ovens

A new comprehensive range of gas-fired tray loading industrial ovens, with a choice of either vertical or horizontal forced air circulation, or natural convection, and of direct or indirect firing, has been introduced by Barlow-Whitney Ltd.

Standard sizes range from 8 to 72 cu.ft capacity, and automatic temperature control is a standard feature. All units incorporate the latest safety features.

STUB ENDS

▶ At the 2nd Annual General Meeting of The Pipeline Industries Guild, held in London on 14th April, Mr. C. C. Bates was elected Chairman of Council, with Captain J. W. Esmonde as Deputy Chairman, and Mr. W. E. Medhurst as Honorary Secretary. The founder of the Guild, Mr. J. W. Jones, was elected an Honorary Life Member.

▶ Students of the Department of Metallurgy of Sheffield University visited the Crawley Works of The A.P.V. Company Ltd. on 9th April, to see the Company's work on the fabrication of stainless steel, aluminium, and other corrosion-resistant metals.

▶ Perdeck Solder Products Ltd. have produced a high-capillary action soldering fluid "Weem No. 130", which has a faster rate of spread than the solder, making it particularly suitable for mechanized soldering processes.

▶ The Fall Meeting of the American Welding Society is to be held in Detroit from 28th September to 1st October 1959. Sixteen sessions will be held and a total of 48 technical papers will be presented.

▶ A brief description of the plasma-jet torch, developed at A.R.D.E. of the Ministry of Supply, is given in the first number of a new periodical "Journal of the Less Common Metals".

▶ The Council for Scientific and Industrial Research announces that in future the Mechanical Engineering Research Laboratory at East Kilbride, Glasgow, will be known as the National Engineering Laboratory. The work of the Laboratory will continue to be concerned with problems of mechanical engineering.

▶ Among recent brochures issued by Kodak Ltd. is one on Photography in Industry and Commerce, which graphically illustrates the important part played by the camera in modern research and technology as well as in the field of advertising. Another brochure describes the properties and applications of new Kodak negative materials suitable for industrial photography.

▶ Weldcraft Ltd., who recently joined the G. D. Peters group of companies, have moved from Croydon to Windsor Works, Slough, Bucks. (Tel.: Slough 23201). With the extensive range of G. D. Peters electric welding equipment added to their own gas welding and cutting lines, Weldcraft state that they are now able to supply "everything for welding".

▶ Mr. D. A. Senior, M.A., A.M.I.E.E., has been appointed to the newly created post of Scientific Attaché to the British Embassy in Moscow. He will advise the British Ambassador (Sir Patrick Reilly) on scientific matters and report on Soviet scientific and technical development in the civil field. Mr. Senior will hold the rank of Senior Principal Scientific Officer, and will be on the staff of the Department of Scientific and Industrial Research.

▶ An agreement has been reached between Harris Calorific Company of Cleveland, Ohio, and British Industrial Gases Ltd., whereby the British Company is allowed to produce and distribute equipment of their design to the world market, excluding Australia, South Africa, and Canada. The first Agent is being appointed in Norway at A/S Sveiseinustri, Bentsebrugt, 15, Oslo.

▶ "Leading the World" is the title of a book recently issued by The British Electrical and Allied Manufacturers' Association. It records the prominent part that the British electrical and allied industries played in the British Industry Pavilion at Brussels and in the British Section at the 'Atoms for Peace' Exhibition in Geneva. This follows the more comprehensive story of British achievements illustrated in the book "Serving the World", which was published for the 1958 Brussels Exhibition.

APPOINTMENTS

Situations Vacant

Welding Engineer required for Sheet Steel and Structural Steel Fabrications for bodywork on Commercial Vehicles. Higher National Certificate standard in Mechanical, Electrical, or Production Engineering is necessary. Applicants who have the ability to improve production methods, introduce jigs and fixtures and who are able to make Time Studies will be preferred.

Applications should be in writing, giving full details of age, education, qualifications, and experience, to the Works Manager, Telehoist Limited, Manor Road, Cheltenham, Glos.

METROPOLITAN-VICKERS ELECTRICAL CO. LTD.

Welding Engineers

Excellent opportunities are available for keen and enthusiastic men with progressive ideas to fill permanent posts in the Company's expanding Welding Engineering Department.

In this Department the work is associated with Welding Machine and Welding Processes, Development and Application Problems, and it would be an advantage to candidates if they have experience in the design or application of welding equipment and processes or in the design of pneumatic and hydraulic control equipment.

A degree in Engineering is required, but qualified engineers with the Higher National in Electrical Engineering who have specialized experience will be favourably considered.

Training

Training will be given to suitable, qualified applicants, who may not yet have the necessary experience but who are interested in welding engineering problems.

Applications, quoting reference C.13 should be sent to:

Personnel Manager
Metropolitan-Vickers Electrical Company Ltd.
Trafford Park, Manchester 17.

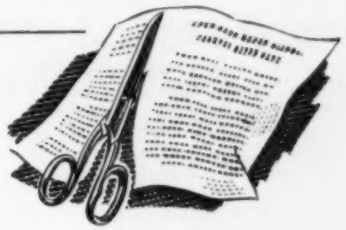
The cost of insertions in this column is 3*s.* 6*d.* a line, or 30*s.* per inch depth semi-display.

Box numbers are added for the additional charge of 2*s.* 6*d.* Replies should be addressed to Box. —, Institute of Welding, 54 Princes Gate, London, S.W.7.

All other matters relating to advertisements for this section of the News should be addressed to the Executive Editor, 6 Ridge End, Hook Hill Lane, Woking, Surrey (Tel. Woking 2981).

Copy should be sent by 6th of each month for publication in the following month.

Current WELDING LITERATURE



Book Reviews

Additions to the Institute Library

Trade Publications

CONTENTS OF PERIODICALS RECEIVED

This section is intended to give a survey of the current welding literature received by the Institute of Welding Library. The contents lists are not exhaustive; only the main articles in welding journals are listed, and reprints from other journals and short notes are generally excluded. In addition, welding articles from other periodicals are listed. Abstracts of welding literature are given in the Bibliographical Bulletin of Welding and Allied Processes, *published by the International Institute of Welding, and details of this may be obtained from the Secretary of the Institute of Welding.*

Welding Journals

Automatic Welding (U.S.S.R. translated by the B.W.R.A.), 1959, March

A new welding process, consumable-nozzle electro-slag welding, G. Z. Voloshkevich, D. A. Dudko, V.V. Chernykh and L. P. Eregin

The manufacture of large diameter vessels from thick plate by the elastic deformation method, G. V. Raevskii

Investigation of the heat resistance of austenitic-ferritic deposited metal Kh19N12M2F, V. M. Zemzin, E. M. Pivnik and N. A. Eroshkin

Consumable-nozzle electro-slag welding, G. Z. Voloshkevich and V. M. Khrundzhe

The gas permeability of welding slags in the electro-slag process, Yu. V. Latash, B. I. Medovar

Added electro-slag metal improves the chemical uniformity of steel castings, G. S. Tyagun-Belous

Spectrographic determination of carbon and phosphorus in steel and weld metal, E. S. Kudelya

The production of a carbon film for electron microscopy, G. F. Darovskii and Yu. B. Malevskii

Spectrographic analysis of welds in aluminium-magnesium alloys, A. S. Demyanchuk and D. P. Ryabushko

Welding current affects porosity in submerged-arc welds made with fluxes of different moisture contents, L. S. Sapiro

Fusing an automatic welding flux in a type DS-0·5 electric furnace, E. I. Leinachuk

Automatic voltage regulator for obtaining stable volt-ampere characteristics for arc welding equipment, V. M. Timofeev and L. S. Surikov

Canadian Welder, 1959, vol. 50, February

Welding for the nuclear power industry (8–10)

Multi-arc welding from a single power source (12–13)

Bridge railings repair, G. P. Lynam (18–19)

Journal of the Japan Welding Society, 1959, vol. 28, January

Welding of plastics, part 1, I. Onishi and H. Kimura (4–10)

Developments of steel filler wires for CO_2 shielded arc welding of low carbon and low alloy steels (11–15)

A study of welding variables of the MIG arc method, A. Uchida (16–21)

Studies of non-metallic inclusions in basic weld metal, part 4, H. Sakaki (22–24)

Welding conditions of steels and cooling time near the fusion line, part 2, M. Inagaki (25–31), **part 3** (32–38)

On the CO_2—Sekiguchi's filler wire arc-welding process, part 9, H. Sekiguchi, I. Masumoto, T. Okada (39–44), **part 10,** H. Sekiguchi and I. Masumoto (45–50)

Weldability of steel coated with various paints, T. Yoshida, W. Matsunaga, F. Kanatani and Y. Ono (51–56)

Przeglad Spawalnictwa (Poland), 1959, No. 2

Fatigue strength of flame-cut elements, T. Robakowski

Oxy-acetylene cleaning of laminated products prior to spot welding, T. Kowalski

Przeglad Spawalnictwa (Poland), 1959, No. 3

Tasks of the Institute of Welding in Gliwica in 1959–1965, B. Szupp

Problems of Polish Shipbuilding industry concerning weldable hull steels, S. Butnicki

On Mohr's strength hypothesis, T. Pelczynski

Schweissen und Schneiden (Germany), 1959, vol. 11, March

Influence of welding on stiffness and damping of welded constructional elements, F. Eisele and H. Drumm (75–83)

Internal stresses, distortions and dimensional accuracy in welding, H. G. Kunz (84–92)

Influence of flame-cutting on fatigue strength, H. D. Steffens (93–97)

Varilna Technika (Yugoslavia), 1958, No. 3–4

Tests of intergranular and atmospheric corrosion on the unstabilized, inoxidizable and welded steel plate 18/8 with 0·085% C (41–44)

Welding in the Soviet Union, N. N. Rykalin (45–50)

The adhesion of metals, D. Uran (50–52)

Modern arc welding of cast iron, J. Babnik (54–57)

Gas-shielded tungsten arc cutting of aluminium, S. Cernetic (58–60)

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Arc welding plants by Philips. Philips Electrical Ltd., Century House, Shaftesbury Avenue, London, W.C.2.

Bonderizing bonds paint to metal surfaces. The Pyrene Co. Ltd., Metal Finishing Division, Great West Road, Brentford, Middlesex.

Kodak "Industrex" high intensity illuminator. A mobile darkroom for photographers and radiologists. Kodak Limited, Kingsway, London, W.C.2.

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Unimer tubular buildings for agriculture and industry. United Merchants Ltd., 418–422 Strand, London, W.C.2.

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Bulk CO_2. CO_2 arc welding. Liquid carbon dioxide. The Distillers Company Limited, Piccadilly, London, W.1.

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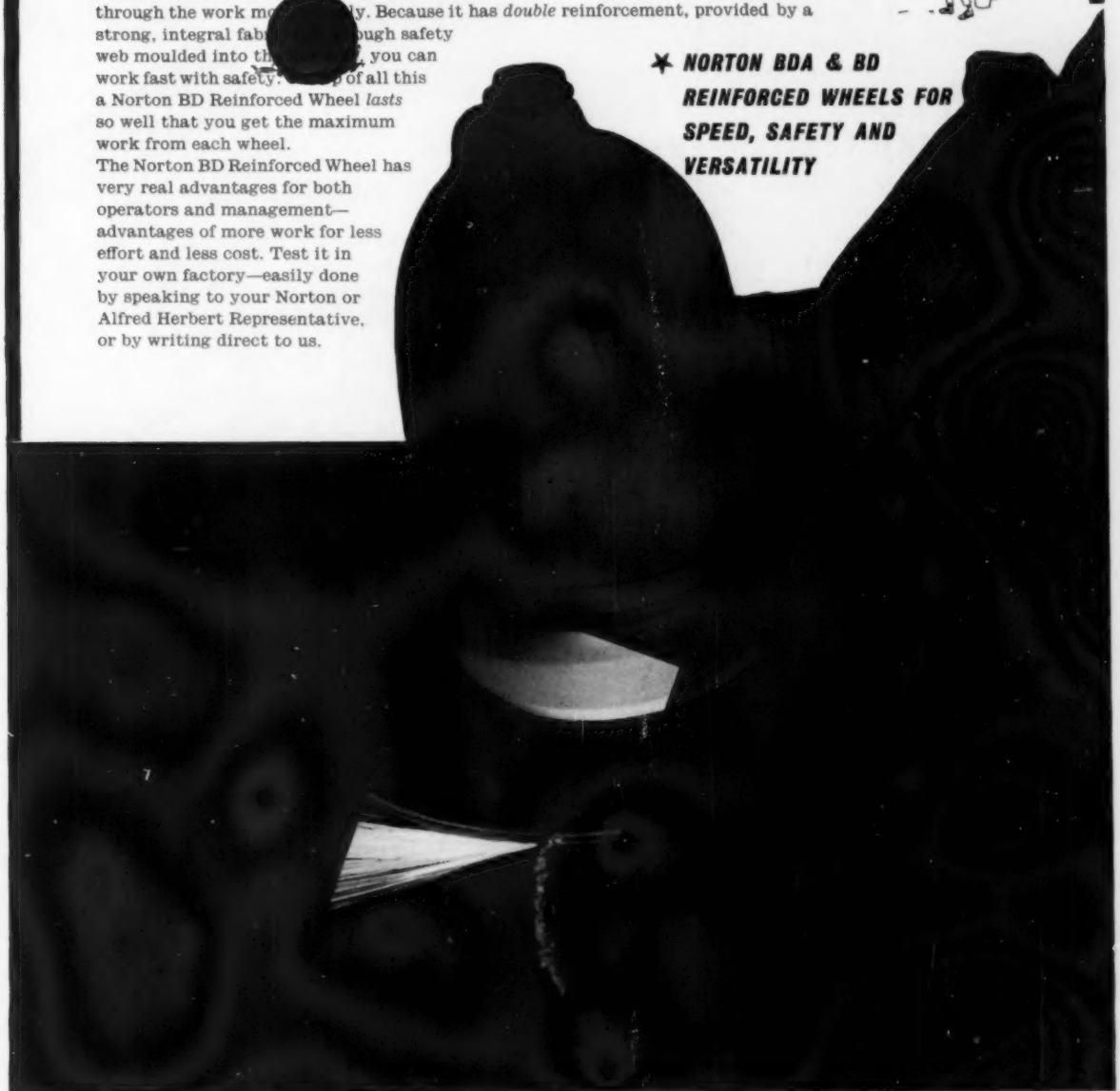

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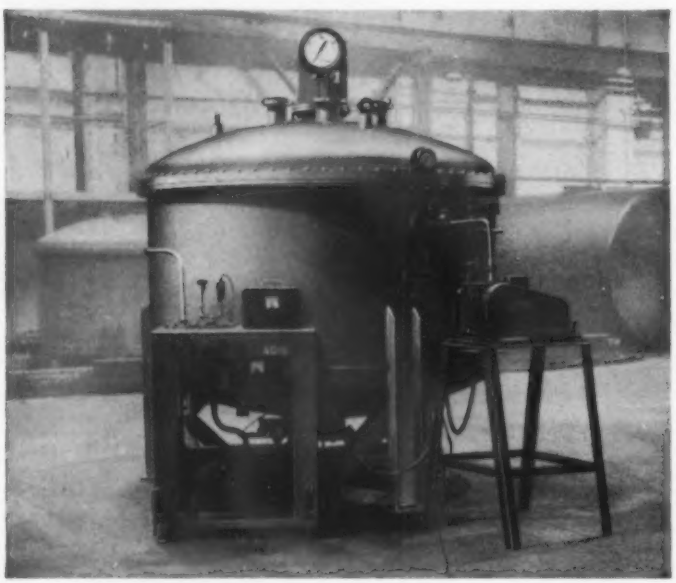

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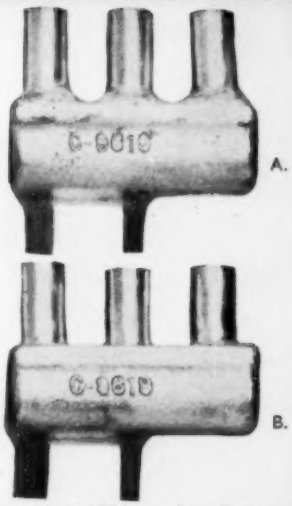

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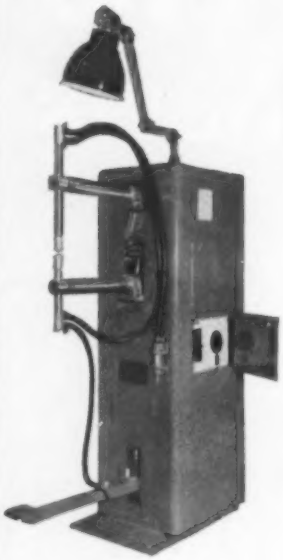

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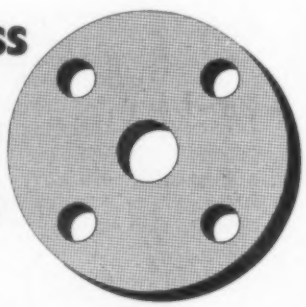

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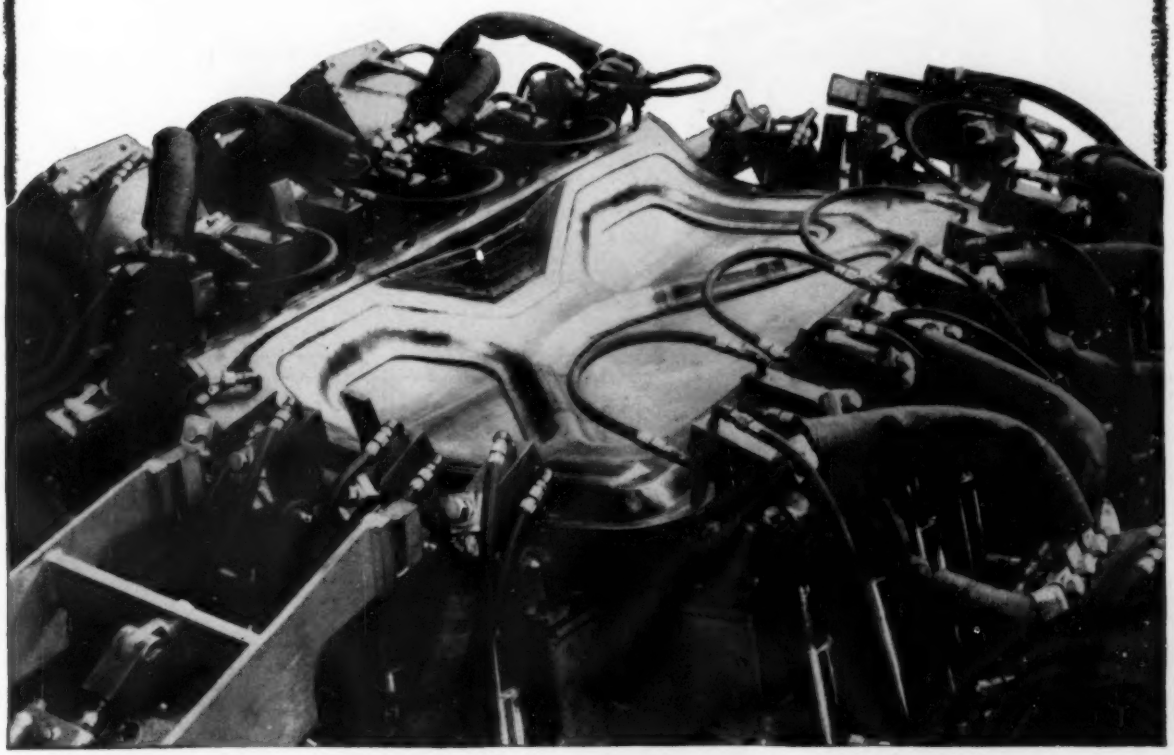

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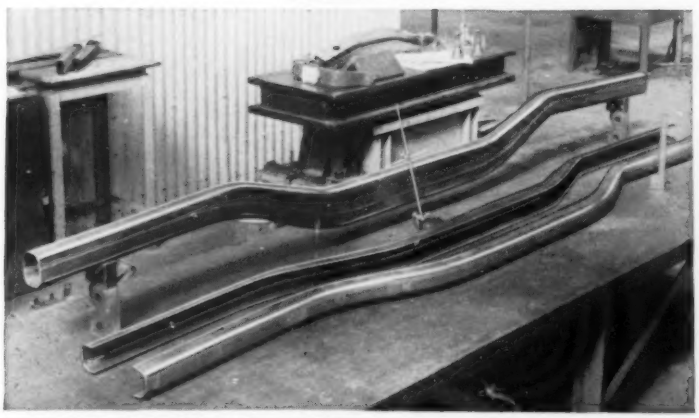

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